AN EXAMINATION OF ELEMENTS NECESSARY FOR TRANSFER OF AN ENVIRONMENTAL REMEDIATION TECHNOLOGY FROM FULL-SCALE DEMONSTRATION TO IMPLEMENTATION

THESIS

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AFIT/GEE/ENV/97D-17

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THESIS

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Degree of Master of Science in Engineering and Environmental Management

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Abstract

The fact that an innovative environmental remediation technology has been proven feasible in a full-scale evaluation does not assure that the technology will be implemented. A number of regulatory, economic, and institutional barriers may impede the transition of a remediation technology from full-scale demonstration to implementation. This research explores these barriers, suggesting means to overcome them.

Regulators, technology users, and other remediation decision makers apply the nine criteria specified in the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) to evaluate the applicability of an innovative remediation technology at uncontrolled hazardous waste sites. These criteria consider such things as cost, implementability, and regulatory compliance of the technology. The usefulness of full-scale technology demonstrations to gather the data required under CERCLA for use by decision makers in evaluating an innovative technology for implementation is explored. Additionally, other mechanisms which may expedite transition of a technology to implementation, such as the use of patents and technology licenses are evaluated for utility. Likewise, the efficacy of information dissemination mechanisms, such as the Internet, are assessed.

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I. Introduction

Background

The first Earth Day celebration was held on 22 April 1970. Eight years later, in 1978, the nation awoke to widespread media attention when it was found that residents of Love Canal were exposed to high levels of dangerous chemicals. A public elementary school and a residential housing development had been constructed on a previous waste site that was now leaking, providing multiple exposure pathways to students and residents. A year later, there was a discovery of literally thousands of barrels of discarded, leaking and unlabeled wastes at the "Valley of the Drums" in Kentucky. All this, combined with other events, such as the spill of pesticides in the James River in Virginia led to increased public awareness and concern over the consequences of environmental damage (Revesz 1995:5).

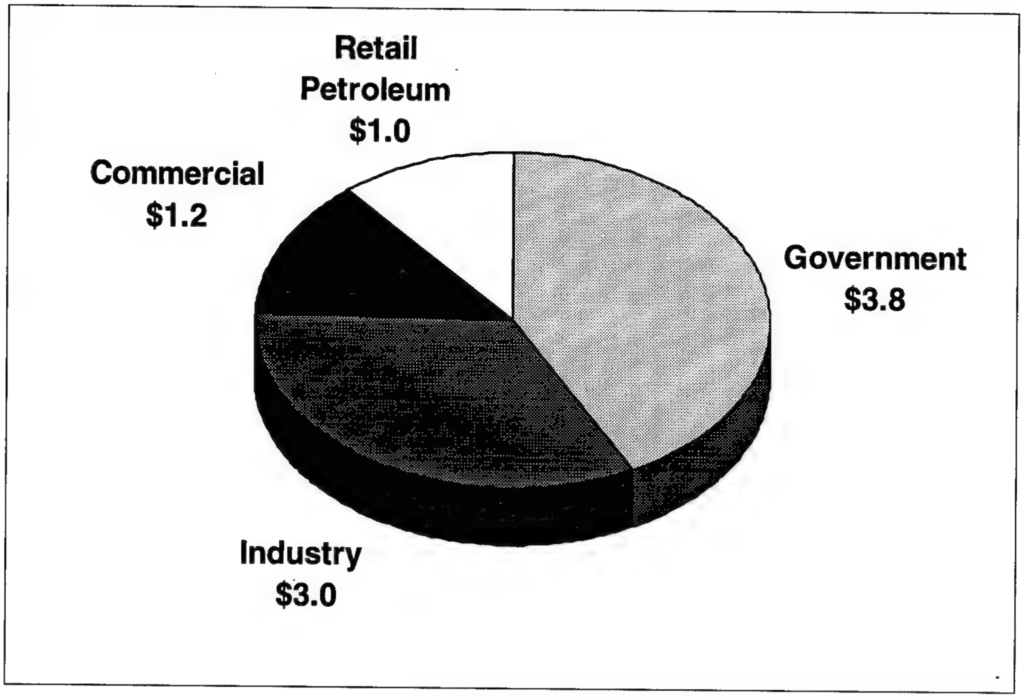
Faced with the situation, Congress acted swiftly during the final months of the Carter administration and with overwhelming bipartisan support passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) which was signed

into law by President Carter on 11 Dec 1980. The goal of CERCLA, commonly referred to as "Superfund", is to respond to situations involving the past disposal of hazardous substances (Lee and others, 1995:225).

Although Congress recognized the need for environmental restoration, few legislators grasped the scope of the nation's cleanup needs. Original funding for CERCLA remediation projects totaled $1.6 billion (Masters 1991:189). Current estimates suggest that cleanup efforts could require the expenditure of several hundreds of billions of dollars (Masters 1991:182). In all, the scope of CERCLA has grown to 1,205 sites nation wide listed on the National Priorities List (NPL), a list identifying the nation's most hazardous sites in need of restoration. The NPL has the potential for an additional 1,400 to 2,300 sites to be added (GAO 1997:2). In addition to CERCLA cleanup efforts being costly, and project scope growing sizably, current remediation strategies are time consuming. In a statement before the House of Representatives, the General Accounting Office Director of Environmental Protection Issues, Peter F. Guerrero indicated that the average time needed to remediate individual sites is 10.6 years (GAO, 1997b:1).

The NPL is not an exhaustive list of the nation's cleanup needs. In fact, 37,000 sites nation wide have been identified with total cleanup costs estimated in 1991 at approximately $752 billion (Astin and Sanders, 1996:55). Shown in Figure 1-1, the National Research Council (NRC) estimates that $9 billion was spent on remediation in 1996 (NRC, 1997:17).

Figure 1-1. Estimated Spending (in billions of dollars) on Environmental Remediation in 1996 (NRC, 1997:18)



This wide-ranging problem has brought on an increased demand for innovative environmental remediation technologies. For example, when the Department of Energy (DOE) cleanup budget for 1991 through 1997 was estimated to approach $41 billion (DOE, 1993:48), a 1994 General Accounting Office (GAO) report cover letter to then-Secretary of Energy, the Honorable Hazel R. O'Leary, stated that "developing less costly and more effective cleanup technologies may be the only way the nation can afford to clean up the vast amounts of waste generated by the nation's nuclear weapons production complex" (GAO, 1994a:1). EPA Administrator, Carol Browner, outlining the EPA's Technology Innovation Strategy indicates that "Perhaps nothing is more essential to achieving our nation's environmental goals than developing and deploying new

technologies for environmental protection. The technologies we have today are not adequate to solve many of today's environmental problems, let alone the challenges that lie ahead (Browner, 1997:1)." In fact, follow-on legislation to CERCLA, the Superfund Amendments and Reauthorization Act of 1986 (SARA), specifically emphasizes the development and use of alternative and innovative remediation technologies (Masters, 1991:252).

Much research and development (R&D) has been conducted in support of the demand for innovative environmental remediation technologies. For example, some innovative technologies for the remediation of groundwater that are currently being demonstrated include air sparaging, bioventing, and metal catalyst dehalogenation, while emerging technologies in the same field include electrokinetics and bioslurping (Gierke and Powers, 1997:200).

The fact that new technologies have been and are being developed to deal with our remediation problems does not mean that those problems are solved. Even new technologies that are capable of attaining regulatory clean-up standards while satisfying time and budget constraints must be implemented in order to be beneficial. Often, new technologies are not given adequate attention by consultants, regulators, and site owners and the technologies are never used (Gierke and Powers, 1997:2). The current trend among federal and state regulators is to fall back on well-known technologies rather than implement innovative technologies that may be more efficient, less costly and, in some

cases, impose less impact on the local environment (Cooney, 1996:432). Moving a technology from the laboratory to field demonstration to full-scale implementation are challenges that must be overcome (Parkinson, 1995:33). Transfering an innovative technology from the full-scale evaluation stage to implementation is a particular challenge (GAOa, 1994:1).

The purpose of this thesis is to define the elements necessary to promote successful transfer of an environmental remediation technology from full-scale field evaluation and validation to implementation. Specifically, factors relevant to the implementation of Department of Defense (DOD)-funded technologies to remediate DOD contaminated sites are considered. This objective complements a statement made by former Secretary of Defense, William J. Perry:

> *Innovative technologies are critical to our country's national and environmental security. Through advanced technology, we can reduce the cost, risk, and time needed to meet the Department's environmental challenges. . . .Many barriers prevent innovative environmental technologies from being implemented at our installations.* (Defense Environmental Restoration Program, 1996)

The barriers impeding implementation of innovative technologies will also be discussed in this thesis, as well as suggested strategies for overcoming these barriers.

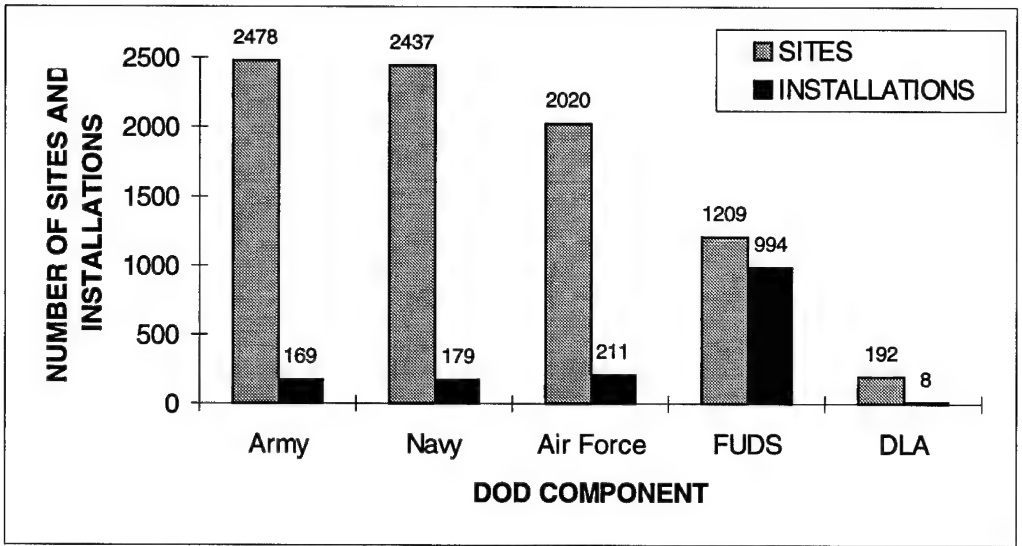
Department of Defense Relevance

For decades, DOD activities and industrial facilities generated, stored, recycled, and disposed of hazardous waste, which often contaminated nearby soil and groundwater

through leaks, spills, or improper disposal methods. In many instances, these problems predate existing environmental laws and regulations. Types of hazardous waste found at most DOD installations include solvents and corrosives; paint strippers and thinners; metals, such as lead, cadmium, and chromium; and unexploded ordnance (GAO, 1995c:10).

Recognizing that military installations are not immune to the environmental consequences of their actions and that environmental legislation was imminent, DOD established the Installation Restoration Program (IRP) in 1975, five years prior to the enactment of CERCLA. The purpose of IRP is to study and remediate DOD contaminated sites. In 1984, this program was made part of the Defense Environmental Restoration Program (DERP), and is currently funded through the Defense Environmental Restoration Account (DERA) (GAO, 1995c:16). Of the 1,205 sites listed on the NPL as of 6 November 1996, 151 are federal sites (GAO, 1997b:2), and at least 126 of those are DOD sites (GAO, 1995a:7). Under DERP, sites identified on the NPL are given highest attention for remediation (GAO, 1995c:12). NPL sites, however, are merely a subset of the 8,336 DOD sites (EPA, 1997a:6-5) requiring remediation at an estimated cost of $30 billion (Astin and Sanders, 1996:55). Figure 1-2 displays a breakdown of DOD sites by component. Figure 1-3 displays the location of DOD sites needing cleanup. The use of innovative environmental remediation technologies can significantly reduce remediation costs while restoring the sites in less time than is required by traditional technologies (GAO, 1994a:1).

Figure 1-2. DOD sites and Installations Needing Cleanup (U.S. EPA, 1997a:6-5)



Note: FUDS = Formerly Used Defense Site; DLA = Defense Logistics Agency

Figure 1-3. Location of DOD Sites Needing Cleanup (U.S. EPA, 1997a:6-6)

The draw-down within DOD and base closures introduced an increased need for timely, and economically attractive remediation technologies. Seventy major domestic military

installations are identified for closure by the Base Realignment and Closure (BRAC) commissions (Greiner, 1996:3). Each of these installations, many containing multiple sites, are programmed for some form of hazardous waste remediation due to the need to restore the sites prior to transfer to local governments or agencies (Baker, 1993:27). The original estimate to restore the sites to a level of environmental compliance was $1.8 billion (GAO, 1995c:2). However, that figure has grown to over $5.3 billion (DOD, 1994) and a recent GAO report indicates that even this figure may be understated by as much as $6 billion (GAO, 1996a:6).

In January, 1995, the Congressional Budget Office (CBO) reported on unanticipated cost growth that has occurred for installations scheduled to close under BRAC. One of the two main reasons blamed for the enormous increase in restoration costs was the lack of use and acceptance of innovative, cost-reducing, environmental remediation technologies (CBO, 1995). Only through the implementation of innovative remediation technologies is it likely that remediation goals will be attained (GAO, 1994a:1).

Air Force Relevance

2,231 of the 8,336 total DOD sites programmed for environmental restoration are Air Force owned and require an estimated $7.4 billion in cleanup costs (U.S. EPA, 1997a:6-12). The Air Force must develop (or acquire) and provide new technologies that meet the regulatory, budgetary, and time constraints for environmental restoration of these sites (Armstrong Laboratory/Environics Directorate 1997:1).

One of the most frequent problems that plagues many DOD installations is the remediation of chlorinated solvent contaminated sites. The Air Force was selected as the DOD lead for remediating sites contaminated with chlorinated solvents because much of the hazardous waste found at Air Force installations includes chlorinated solvents used in paints, strippers, and thinners (GAO, 1995c:10). Trichloroethylene (TCE), a chlorinated solvent, was used extensively as a metal degreaser for aircraft. Nationwide, the most frequently detected groundwater contaminant at U.S. hazardous waste sites is TCE (National Research Council, 1994). One innovative technology that has been developed in the laboratory and is currently undergoing full-scale evaluation for remediating TCE-contaminated sites is *in situ* aerobic cometabolic bioremediation. This technology will subsequently be examined in some detail, as it will provide us with a "real-world" case study to show how a technology may be transferred from full-scale evaluation to implementation.

Definition of Terms

Some specific terminology is used to describe the movement of environmental remediation technology from development to implementation. The following list of terms will be employed throughout this thesis.

> Remediation Technology Development - The process of moving from conceptual stages of an environmental cleanup product or process to laboratory verification and documentation, and finally to full-scale evaluation, validation, and documentation. The primary goals of remediation technology development projects are to: elucidate rate limiting phenomena, verify conceptual and

mathematical models of the process, and identify site characteristics critical for the successful implementation of the technology (Gierke and Powers, 1997:199).

Emerging Treatment Technology - An environmental remediation technology that is chronologically in the early stages of development. Typically, *emerging* implies that the technology has not yet progressed beyond laboratory or controlled field experiments (Gierke and Powers, 1997:200).

Environmental Remediation Technology - A process or product that aids or accomplishes the cleanup or removal of a toxic spill or hazardous materials from a Superfund site (U.S. EPA, 1997c:1). In this research, this definition is enlarged to include a process or product that aids or accomplishes the cleanup or removal of a toxic spill or hazardous material from any site at a DOD installation (DOD-owned Superfund site, BRAC installation site, IRP site, underground storage tank (UST) site, etc.).

Full-Scale Evaluation - A field-scale demonstration allowing for observation of large-scale effects and other nonideal conditions that may not be incorporated in the spatial and temporal scale of laboratory experiments (Gierke and Powers, 1997:198). Full-scale evaluations, an important phase of remediation technology development, have the capacity to elucidate rate-limiting phenomena, verify conceptual and mathematical models of the processes, quantify design parameters, and define the conditions where the application of the technology is appropriate (Gierke and Powers, 1997:196).

Implementation - The application of an environmental remediation technology to cleanup or remove a toxic spill or hazardous materials from a Superfund or other similar hazardous waste site, including BRAC sites, IRP sites, and UST sites.

Innovative Treatment Technology - A technology for which applications at Superfund and other similar hazardous waste sites are inhibited by lack of data on performance and cost. In general, a technology is considered innovative if it has limited full-scale application (U.S. EPA, 1994).

Technology Transfer - The progression of product or process from a research and development phase to its embodiment in a system or production process for operational use by an organization *external* to the developing organization. Although a distinction exists between the transfer of technology (external to the developing organization) and the transition of technology (internal to the developing organization), technology transfer will be used synonymously with technology transition in this thesis as defined below.

Technology Transition - The progression of product or process from a research and development phase to its embodiment in a system or production process for

operational use by a function *internal* to the developing organization. Technology transition will be used in this thesis to define the progression of an environmental remediation technology from a government-funded research and development phase to its use by a government organization for site remediation. The application of the technology may be carried out by an *external or internal* organization.

Validation - An assessment to verify the efficacy of an environmental remediation technology through the employment of properly designed controls and analytical methods so that observed reductions in contaminant concentrations can be attributed specifically to use of the environmental remediation technology (Gierke and Powers, 1997:196).

Research Objectives

The objective of this research is to identify factors relevant to the transfer of innovative environmental remediation technologies from development to implementation in order to facilitate the use of these technologies for timely, cost effective remediation of DOD sites. Specifically, the objectives of this research are:

1) To identify the barriers to transferring an environmental remediation technology from field evaluation to implementation, as well as the elements necessary to overcome those barriers, in order to apply the technology to remediate DOD contaminated sites.

2) To present *in situ* aerobic cometabolic bioremediation as an example of an innovative technology currently being evaluated in the field in order to demonstrate strategies and techniques that may be useful in transitioning the technology to full-scale implementation.

Scope of Research

This research effort focuses primarily on the transition of Government-funded environmental remediation technologies from full-scale demonstration to DOD site applications. However, the insight gained from research into the transfer of these

technologies may also be useful to organizations other than the DOD. For example, in a 1994 United States General Accounting Office (GAO) report to the Secretary of Energy it was concluded that "Although the Department of Energy (DOE) has spent a substantial amount to develop waste cleanup technology, little new technology finds its way into the agency's cleanup actions."(GAOa, 1994:1) Clearly, this research is also applicable to DOE environmental restoration.

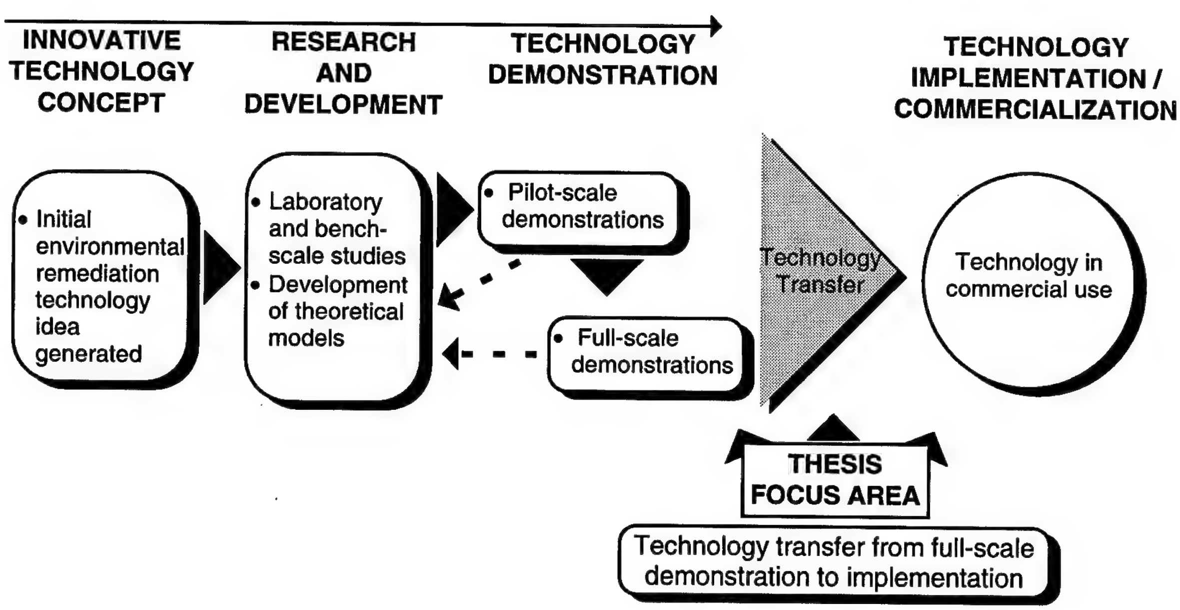
II. Literature Review

Introduction

The purpose of this chapter is to provide a brief overview of the literature relevant to the transfer of an environmental remediation technology from full-scale demonstration and evaluation to implementation.

To properly explore the literature applicable to this thesis, the relevant step in the progression of an innovative environmental remediation technology from concept to implementation must be defined. Figure 2-1 shows the progression of an innovative environmental remediation technology and highlights the focus area of this thesis, transfer of an environmental remediation technology from full-scale demonstration to implementation.

Figure 2-1. Progression of an Environmental Remediation Technology from Concept to Implementation (after Gierke and Powers, 1997:198)



Gierke and Powers (1997:199) have developed a table, Table 2-1, outlining the attributes of each step in the progression.

Table 2-1. Steps in the Development and Implementation of an Innovative Environmental Remediation Technology and Corresponding Attributes (after Gierke and Powers, 1997:199)

STEP IN DEVELOPMENT PROCESS	ATTRIBUTES
Innovative Technology Concept	• Idea generated
Research and Development	• Development of theoretical models • Laboratory experimentation • Very controlled settings
Technology Demonstration - *Pilot-Scale*	• Small field plots • Some uncontrolled parameters • Collection of data for model calibration
Technology Demonstration - *Field-Scale*	• Uncontrolled setting • Extensive data collection • Verification of predictive models
Technology Implementation / Commercialization	• Commercial application • Compilation of cost information • Development of general guidance documentation

As Figure 2-1 suggests, the progression of an innovative environmental remediation technology is not a linear process. As information is learned during the technology demonstration phases, that information is fed back to the research and development phase to design further laboratory studies, answer additional questions, and calibrate or verify predictive models. Once a technology has been successfully demonstrated, a crucial step in the progression of an innovative environmental remediation technology must take place, transfer of the technology for implementation at contaminated sites –the focus of this thesis.

Research Motivation

As discussed in Chapter 1, there exists a need for implementation of innovative environmental remediation technologies. Currently accepted technologies often fail to restore a contaminated site in a manner that is timely, economically practical, and effective. This fundamental problem, which is acknowledged in numerous government and private publications, forms the basis for this thesis.

Government publications supporting the need for better environmental remediation technologies and better methods of environmental remediation technology transfer are abundant. They include numerous GAO and EPA reports as well as reports issued by the CBO and DOD (GAO, 1994a, 1995a, 1995b, 1996a,1996b, 1997b; EPA, 1994; CBO, 1995; DOD BRAC, 1994). The GAO is an unbiased research agency that has conducted a significant amount of research related to the subject of environmental restoration. Table 2-2 provides a chronological listing of the most pertinent recent GAO publications and a short summary of relevant conclusions offered in each report.

As is the case with government publications, non-government publications supporting the need for innovative environmental technologies and sound practices for their transfer are plentiful. For example, Gierke and Powers suggest field-scale performance assessments as a method of technology transfer (Gierke and Powers, 1997:196). In "Overcoming Barriers to Technology Transfer," Baron offers a review of and suggests remedies for common technology transfer barriers (Baron, 1990:38). These, and other private-sector publications will be further reviewed in this chapter.

Table 2-2. Pertinent Recent GAO Publications

PERTINENT RECENT GAO PUBLICATIONS		
DATE	**TITLE**	**RELEVANT CONCLUSIONS**
10 August 1994	*Department of Energy: Management Changes Needed to Expand Use of Innovative Cleanup Technologies*	• More advanced environmental remediation technologies are needed. • Field decision-makers often neglect new technologies, preventing promising new techniques from being used to clean up sites.
24 March 1995	*Environmental Protection: Challenges in Defense Environmental Program Management*	• Technology limitations hamper more timely and cost-effective cleanup. • Conflicting priorities prevent the approval of innovative approaches for cleanup. • Field officials may associate newer technologies with unacceptable levels of risk. • On-site contractors may favor particular technologies on the basis of their own experience and investments. • Lack of cooperation between federal agencies greatly increases the amount of time and money required to study and clean up contaminated sites.
23 Feb 1995	*Military Bases: Environmental Impact at Closing Installations*	• New and better cleanup technology is needed .
26 June 1996	*Energy Research: Opportunities Exist to Recover Federal Investment in Technology Development Projects*	• Cost-shared projects to demonstrate the capability of industry technologies can be beneficial to the government and industry.
5 Sept 1996	*Military Base Closures: Reducing High Costs of Environmental Cleanup Requires Difficult Choices*	• Restoration of BRAC sites is estimated to exceed 11 billion dollars. • Available cleanup technology is not cost-effective. • New cleanup technologies represent the best hope of addressing environmental problems with available DOD funds.
7 May 1997	*Cleanup Technology: DOE's Program to Develop New Technologies for Environmental Cleanup*	• Use of 41 innovative technologies would result in DOE cost savings from $476 million to $490 million

Categories of Technology Transfer

A well published author of technology transfer research, Robert Carr, suggests three categories that encompass the realm of technology transfer: market pull, technology push, and modified technology push (Carr, 1992a:12).

Market Pull: The current focus in federal technology transfer is on industry-led or market-pull transfer. Market-pull technology transfer is a process by which a private business seeks the development of a particular technology by a federal laboratory for an application defined by the private sector business. This usually only occurs when the technology has applications in both the private and public sectors. This type of technology transfer is usually appealing to private industry since they have a significant role in the R&D underlying the resulting technology. Since the private sector is in the lead, it is extremely probable that the resulting technology will be successfully transferred (Carr, 1992a:12).

Technology Push: Although there is enthusiasm for market-pull technology transfer, it is important to note that most new technologies, particularly the breakthroughs, have emerged through laboratory discoveries being pushed toward the private sector, technology-push. Carr suggests that most scientific discoveries are unexpected, and not the result of directed research. Thus, laboratory technology transfer programs should remain structured to handle technology-push, as well as market-pull transfers (Carr, 1992a:12).

Modified Technology Push: Modified technology push occurs when a research institution or laboratory promotes technologies for which a commercial market is known to exist (Carr, 1992a:12). Of the three categories suggested, this category may be most applicable to environmental remediation technologies. As presented in Chapter 1, the demand for these technologies is well known. Thus, laboratories often develop cleanup

technologies in the absence of direct interest from a commercial firm, but with the knowledge that there is almost certainly a customer for the technology.

Environmental Technology Transfer Stakeholders

For an environmental remediation technology to evolve from a concept to full-scale implementation, a range of stakeholders must be convinced of the technology's ability to perform. Expectations about how well a technology should perform and in what categories (cost, safety, implementation, etc.) performance is most important may vary widely among stakeholder groups: the public, regulators, and technology users.

Public

This group consists primarily of people living near the contaminated site. An active local community who finds the implementation of a selected environmental remediation technology unacceptable is capable of stopping its use (NRC, 1997:158). Additionally, although the public at large may be concerned about the cost of remediation efforts nationwide, local communities that have a contaminated site (and where remediation costs are not directly absorbed by the local community) are usually more interested in identifying the most effective technology, regardless of cost. It is not uncommon for members of the local community to be discontent with efforts by government agencies or responsible parties to minimize cleanup costs, especially if the community members feel that they have suffered health effects or that damage to natural resources has occurred (NRC, 1997:158).

Other factors often important to the local community include the safety of the technology and the degree to which it disrupts the local community. For example, the use of *in situ* flushing technologies such as surfactant technologies may cause the uncontrolled migration of contaminants to subsurface zones not previously contaminated, possibly increasing the health risk to community residents. Technologies that require local traffic to be rerouted or yards to be excavated are given careful thought by the local community. Community members may find these inconveniences greater than the benefit gained by remediating the contaminated site (NRC, 1997:160).

Regulators

Regulators are most concerned with being assured that a selected cleanup remedy is capable of meeting various statutes governing the site cleanup, including CERCLA, the Resource Conservation and Recovery Act (RCRA), and other state-level equivalents of these programs (NRC, 1997:161). Most statutes have criteria for technology selection similar to the CERCLA evaluation criteria (discussed later in this chapter). Because regulatory agencies are often the target of public attacks due to failed remediation efforts, regulators are careful to be tuned to the desires of the local community and most interested in environmental remediation technologies that perform well over a range of geological conditions and are safe –hence lessening the probability of conflict with the local community (NRC, 1997:161).

Technology Developers

Developers of environmental remediation technologies may engage in the field for many reasons including interest in solving complex problems that have a real-world application, hopes of monetary profit, or belief that the approach they have conceived can meet objectives better, faster, and cheaper than conventional technologies. Whatever their reason for undertaking development efforts and regardless of where they pursue their interests (academic institutions, government labs, etc.), the implementation of remediation technologies is largely influenced by regulation (NRC, 1997:162). It is, therefore, important that technology developers demonstrate that their technology is capable of meeting regulatory requirements. In many instances, technology developers have financial interest in promoting widespread use of their technology. To reach a large sector of the environmental remediation technology market, developers clearly must demonstrate that their technology is applicable under a wide range of conditions and competitive with technologies that address the same contaminant groups (NRC, 1997:162).

Technology Users

Users of environmental technologies (those responsible for cleaning up a contaminated site) are often reluctant customers. Described later in this chapter, technology users (site owners) often take a variety of actions to defer using any remediation technology at all due to incentives to delay cleanup. After exhausting all alternatives to remediating a contaminated site, site owners often focus on the selection of a technology that meets regulatory standards as cost effectively and expeditiously as possible (NRC, 1997:162).

The technology user has a strong interest in the environmental remediation technology working right the first time and is concerned about the technology's ease of implementation, robustness over a range of site conditions, ability to handle variable waste streams, minimization of interference with ongoing activities at the site, and ease of maintenance (NRC, 1997:162).

Consultants

Consultants are individuals specializing in site characterization and technology recommendation. Most commonly, consultants work for a private firm that is hired by a site owner needing the environmental expertise of the consultant to determine the proper course of action to remediate a site. Because of this relationship, the desires of a particular consultant will closely parallel those of the site owner (described above) that has hired the consultant.

For an environmental remediation technology to be transferred to full-scale implementation, the concerns of each of the stakeholder groups must be adequately addressed. The NRC suggests that stakeholder concerns fall into three main categories: technical performance, commercial characteristics, and acceptability to the public and regulators (NRC, 1997:157). Table 2-3 presents the level of stakeholder concern about remediation technology performance in each sub-category encompassed in these three main categories.

Table 2-3. Stakeholder's Concerns About Remediation Technology Performance (After NRC, 1997:159)

TECHNOLOGY PERFORMANCE ATTRIBUTE	STAKEHOLDERS			
	PUBLIC	REGULATORS	TECHNOLOGY USERS	TECHNOLOGY PROVIDERS
TECHNICAL PERFORMANCE ATTRIBUTE				
Reduction in health and environmental risk	*H*	*H*	*H*	*H*
Robustness[a]	-	*M*	*H*	*H*
Forgiveness[b]	-	*L*	*H*	*H*
Ease of implementation	-	*L-M*	*H*	*H*
Maintenance; down time	-	*M*	*H*	*H*
Predictability; ease of scaleup	*M*	*H*	*H*	*H*
Secondary emissions and residual production	*H*	*H*	*M*	*M*
COMMERCIAL CHARACTERISTICS				
Capital costs	*L*	*M-H*	*H*	*M*
Operating costs	*L*	*M-H*	*H*	*M*
Copyright, patent restrictions	-	-	-	*H*
Profitability	-	-	-	*H*
Accessibility	*L-M*	*M-H*	*M-H*	*H*
ACCEPTABILITY TO THE PUBLIC AND REGULATORS				
Disruption to community	*H*	*M*	*M*	-
Disruption to ongoing site activity	*M*	-	*H*	-
Safety	*H*	*M*	*H*	-
Regulatory hurdles	*H*	*M*	*H*	-
Future useability of the land	*H*	-	*M-H*	-

Note: "H" denotes a high, "M" denotes a medium, and "L" denotes a low level of interest in the indicated technology performance attribute. A blank entry, "-", no or very minimal concern about the particular performance attribute.
[a]Robustness refers to a technology's ability to operate over a range of environmental conditions.
[b]Forgiveness refers to a technology's sensitivity to operating conditions.

Technology Transfer Models

A number of technology transfer models have been introduced to describe mechanisms of transfer. Most of these models, however, have limited application to environmental remediation technologies. Therefore, a discussion of these models will not be presented here. For the interested reader, two references which capture the many non-environmental technology transfer models are Crutcher and Fieselman (1994), and Rose (1995). Although the literature search failed to uncover any technology transfer models specific to environmental remediation technologies, three models were discovered that

specifically address federal laboratories. The models include the legal model, administrative model, and the marketing model (Carr, 1992a:16).

Legal Model

Legal model technology transfer programs are often referred to as patenting programs. This model focuses on patenting inventions. Carr suggests that this model was the most common among federal laboratories prior to technology transfer legislation (relevant legislation will be covered later in this chapter). It is also noted that this model proved unsuccessful prior to legislation because licensing of public discoveries was required to be nonexclusive. Few firms were interested in investing in, and marketing, federal technologies since there was little protection of their investment without an exclusive license (Carr, 1992a:16). There is still debate over the effectiveness of this model, especially as it pertains to environmental remediation technologies. Some light will be shed on this subject in the results section of this thesis.

Administrative Model

Following the technology transfer legislation of the 1980s, federal laboratories began to move toward the administrative model. This model employs administrators, rather than lawyers (as is typically the case in the Legal Model), as technology movers. The focus is still on patenting the technology, however, more attention is paid to the commercial potential prior to patenting. Exclusive licenses are commonly granted for technologies that require significant additional development for commercialization (Carr, 1992a:16).

Marketing Model

Under the marketing model, technology transfer centers/functions must accumulate and have on hand a significant inventory of technologies to market to industry. Federal inventors are encouraged to disclose their inventions through a simplification of the patent process and rewards in the form of royalty income or other incentives. Marketing Model technology transfer offices are focused on finding an appropriate licensee and concluding a license agreement expeditiously (Carr, 1992a:16).

The three technology transfer models addressed all include patenting of the technology in one form or another. A patent is an agreement between the government and the inventor whereby, in exchange for the inventor's complete disclosure of the invention, the government gives the inventor the right to exclude others from making, using, or selling the invention for a period of twenty years (DOE Office of Environmental Management, 1997:10). Items that may be patented include

- **Process** - Any process, art, or method of achieving a physical or chemical change in the character or condition of an object.
- **Machine** - Any apparatus or mechanical device with interrelated parts that function in conjunction with one another.
- **Manufacture** - All articles that are manufactured or made.
- **Composition of Matter** - Chemical compounds or mixtures of substances that have properties different from those of individual ingredients years (DOE Office of Environmental Management, 1997:10).

Environmental remediation technologies are often processes. Much of what Carr focused on were machined items. As indicated earlier, there is debate over the efficacy of patenting environmental remediation technologies (processes) –although the number of environmental patents issued annually is rising (Table 2-4) . This subject will be specifically addressed in the results section of this thesis.

Table 2-4. Remediation Technology Patents Issued (NRC, 1997:59)

TIME PERIOD	PATENTS REFERRING TO "REMEDIATION"	PATENTS IN CLASS 588: HAZARDOUS WASTE DESTRUCTION OR CONTAINMENT
1976 - 1980	*1*	*0*
1981 - 1985	*0*	*0*
1986 - 1990	*9*	*1*
1991 - 1992	*25*	*13*
1993 - 1994	*82*	*348*
1995 - 1996 (8 months)	*88*	*263*

Technology Transfer Methods

Documented methods of technology transfer are abundant (Carr, 1992a; Souder *et al.*, 1990; Winebrake, 1992; Griener, 1996) with different methods appropriate at different stages of the technology research and development process. The focus of this thesis is on the transition of an environmental remediation technology from full-scale demonstration to implementation. Because of this focus, the use of full-scale technology demonstrations will be discussed in detail following a discussion of other methods of technology transfer. It is appropriate that methods other than that of technology demonstrations be addressed because no single method can stand alone. It is often the synergistic effect of the combination of methods that leads to a successful transfer.

Some of the most common methods of technology transfer are compiled by Rood (Rood, 1989). Although her work is nearly a decade old, more recent literature offers little additional material nor is it compiled in a single comprehensive work. Rood offers seven strategies for promoting and accelerating technology transfer. These methods include: intermediary mechanisms, decentralized invention management, cooperative research, patent waivers, personal incentives, personnel-exchange programs, and foreign patent rights (Rood, 1989:16). Although her research is centered on technology transfer by the federal government, her work is not specific to the environmental remediation arena. However, the methods defined are general approaches to technology transfer and, except for foreign-patent rights, are applicable across many technology fields, including environmental remediation technologies. Because foreign-patent rights focus on the transfer and commercialization of technology in foreign countries, it has little application to this research, methods of transfer for environmental remediation technologies to be employed at DOD installations, and therefore will not be presented. It should also be noted that each method is not meant to "stand alone." More common in successful technology transfer is the use of many methods, overlapping one another.

Intermediary Mechanisms

The goal of intermediary mechanisms is to match technology users with laboratory technologies. Intermediaries can be useful in ensuring that users and providers of technologies successfully communicate with each other by translating the problem or by suggesting new applications for existing technologies. In the most basic definition, intermediaries are offices with the primary function of administering technology transfer.

Intermediaries may be formed within the laboratory organization, or the laboratory may rely on the services of a private technology broker (Rood, 1989:16).

Decentralized Invention Management

Invention management involves identifying, screening, and evaluating technologies with commercial potential and then patenting the technologies, marketing the patents, and negotiating licenses for the right to use the technologies. Decentralized invention management, as encouraged by the FTTA, is the placing of these roles and functions at the level of individual laboratories, as close to the inventor as possible. This method hopes to accelerate technology transfer by placing the process in the hands of those who most intimately understand the technology (Rood, 1989:17).

Cooperative Research

At the institutional level, cooperative research arrangements contribute to technology transfer because the technology user is involved in the process of technology development from its earliest conception. Cooperative efforts/teaming among organizations in the research and industrial sectors include simple one-on-one laboratory-firm arrangements, or they can be more complex, such as federal-laboratory/multi-firm consortia; federal-laboratory/university consortia; and federally-supported, university-based/multi-firm consortia (Rood, 1989:17).

Patent Waivers

In some instances, the government may forego the rights to a technology and pass the title to a private organization assisting in the technology invention. This strategy encourages the transfer and commercialization of the technology, particularly for use in government applications, through providing the private firm with an economic incentive (Rood, 1989:18). Licensing, a somewhat related mechanism, is described by the DOE Office of Environmental Management as "the transfer of intellectual property rights to a third party for purposes of commercialization." Licensing can be exclusive or non-exclusive, for a specific field of use, or geographical area (DOE, 1997:19).

Personal Incentives

The function of transferring technologies is usually a secondary mission to most research organizations since their primary mission is research. In an effort to overcome this hurdle, and encourage federal managers and employees to be more aggressive in transferring technologies, some incentives may be employed. For example:

- Royalties for federal inventors to motivate them to be more active in finding commercial applications for their research.
- Financial incentives for researcers engaged in mission oriented research to focus some of their efforts toward technology patents and commercialization.
- Incentives for middle management to be interested in promoting technology transfer (Rood, 1989:18).

Personnel-Exchange Programs

Rood suggests that personnel-exchange programs could make it possible for government scientists and engineers to temporarily work in private industry on collaborative research efforts. However, at the time of Rood's publication (1989), temporary transfer of agency personnel to industry was not permitted except under a leave of absence or equivalent arrangement (Rood, 1989:18). Since then, personnel-exchange programs between government and industry have been permitted and are a viable method of technology transfer (DOE, 1997:19).

James J. Winebrake, author of "A Study of Technology-Transfer Mechanisms for Federally Funded R&D", offers a semi-quantitative study of technology transfer methods. This study reviewed the technology transfer level of success of 116 DOE projects. DOE staff members involved with a particular project were asked to identify from a list of 25 example mechanisms used in the technology transfer process. The examples were grouped according to common characteristics, reducing the list to seven general mechanisms. This list is shown in Table 2-5.

The respondents were directed to rank each general mechanism that was employed on a scale from 1 to 5, 5 being "very effective" and 1 being "not very effective." The study revealed that of the seven general mechanisms, two emerged as the most successful, "Advisory Groups" and "Collaboration with Cost Sharing" (Winebrake, 1992:57). Advisory groups usually include technical experts, members from industry, marketing strategists, and, when practical, end users. Use of advisory groups ensures

communication between all interested parties (Winebrake, 1992: 57). This supports the finding of another study that concluded that two major barriers to technology transfer in federal laboratories are: (1) the expectations of one party are not always shared by the other party, and (2) there often exists a lack of awareness of the value of the technology being transferred (Debruin and Corey, 1988:62).

Table 2-5. Technology Transfer Mechanisms (after Winebrake, 1992)

GENERAL	EXAMPLES
Advisory Groups	*End User Review Groups* *Technical Review Groups*
Collaboration With Cost-Sharing	*Industry Consortia* *Cooperative R&D* *Demonstration Projects* *User Facilities*
Collaboration Without Cost-Sharing	*Contracting R&D*
Personnel Exchanges	*Work for Others* *Staff Consulting* *Guest Staff* *Staff Transfers*
Licensing/Spinoffs	*Licensing* *Spinoff Companies*
Dissemination of Information	*Broker Organizations* *Workshops, Seminars, or Conferences* *Information Centers* *Education* *Mailings* *Technical Reports* *News Releases* *Journal and Magazine Articles* *Fact Sheets* *Videotapes* *Decision Tools* *Electronic Bulletin Boards*

Collaboration with cost sharing is the second mechanism found to be important to the success of technology transfer though the category "Collaboration without Cost Sharing"

did not prove to be a significant mechanism for ensuring success. This suggests that the method of collaboration is as important, if not more so, than the collaboration itself. Winebrake offers four possible explanations for this phenomenon:

1. Cost-sharing (and the potential financial losses associated with it) forces recipients to look more carefully at a project before entering a collaborative agreement, and only those projects showing high success potential are chosen.

2. Cost-sharing may attract recipients with money already invested in the technology elsewhere or in some other form, and these recipients bring with them experience that successful transfers need.

3. Cost-sharing assures that certain intellectual-property rights or licenses remain protected, and hence, the potential profit incentive of these projects remains.

4. Cost-sharing breeds a commitment by both parties to make a project work because only successful projects bring returns to the investor (Winebrake, 1992:59).

In "Doing Technology in Federal Laboratories (Part 1)," Robert Carr presents a survey which reveals that responding companies thought that promising interactions with federal laboratories would come from visits to laboratories, information dissemination by laboratories, technical consultation, workshops, seminars, and cooperative research, in that order. Licensing, contract research, and employee exchange were ranked as least likely to have future payoffs (Carr, 1992a:11). Interestingly, the categories ranked highest by companies, visits to laboratories and information dissemination, are not easily placed in any of the broad categories identified by Rood and were not ranked as statistically significant by Winebrake. Again, it is emphasized that mechanisms of technology transfer are not easily defined, and can rarely be considered as "stand alone" entities. The

success of a method in one industry is not a guarantee of similar performance in another industry.

World Wide Web

Both Winebrake and Carr identify information dissemination as an important method of technology transfer. One very recent method of information dissemination, use of the World Wide Web, warrants discussion. The advent of the World Wide Web has provided opportunities for information dissemination far beyond any means of the past. Many federal and private agencies have taken initiatives to provide internet sites with the purpose of aiding in the transfer of environmental remediation technologies. Table 2-6 is a brief list of some of these sites. Although nothing specifically was found in the literature pertaining to the utility of these sites, the abundance of them justify their inclusion in this thesis. Due to its newness, it is difficult to predict the ultimate fate of this means of information dissemination or what role the World Wide Web will play in the transfer of environmental remediation technology. This topic will be addressed in more detail in the results section of this thesis.

Table 2-6. Partial List of Environmental Remediation Technology Transfer Internet Sites

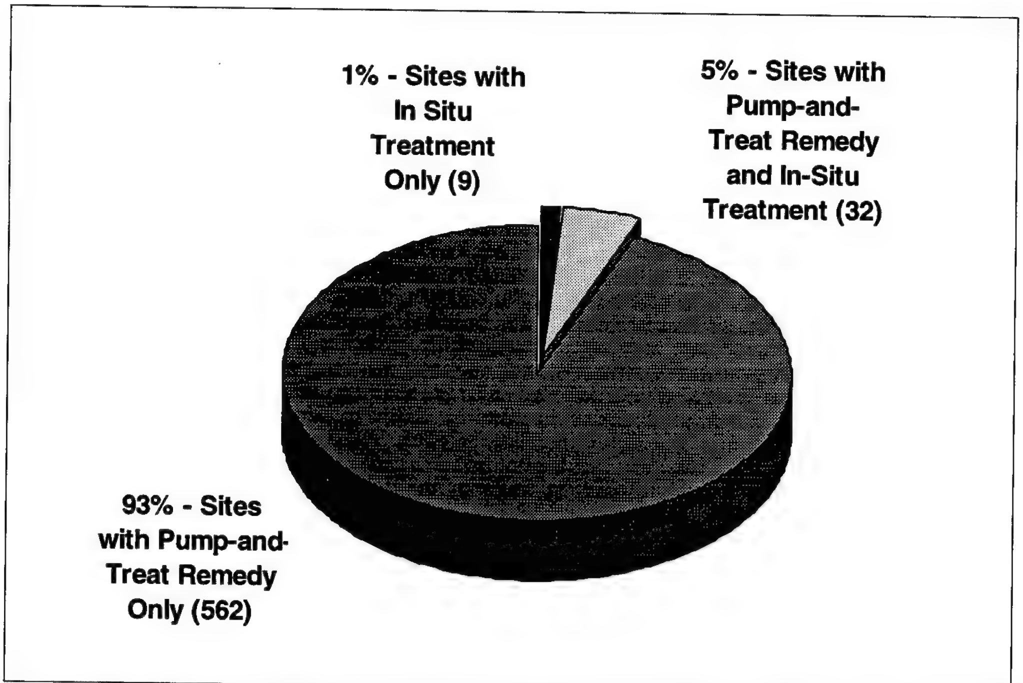
SITE NAME / OWNER	MISSION / SERVICES OFFERED
Defense Environmental Network & Information Exchange *United States Department of Defense* http://denix.cecer.army.mil/denix/denix.html	Designed to provide DOD personnel with timely access to environmental legislative, compliance, restoration, cleanup technology, safety & occupational health, security, and DOD guidance information
Environmental Management *United States Department of Energy - Office of Environmental Management* http://www.em.DOE.gov/index.html	Responsible for environmental restoration, waste management, technology development and transfer, and facility transition and management within the DOE
Environmental Technology Initiative *United States Environmental Protection Agency* http://www.epa.gov/oppe/eti/eti.html	Environmental technology initiative supporting more than 250 environmental technology partnerships and projects throughout the United States demonstrating innovative environmental remediation technologies
Environmental Technology Transfer *National Technology Transfer Center (NTTC)* http://www.nttc.edu/environmental.html	NTTC, established by Congress, is the hub of a national network linking U.S. companies with federal laboratories to turn government research into practical, commercially-relevant technology. Services offered include links to federal laboratories, regulatory information, and consolidation of innovative technologies.
Hazardous Waste Clean Up Information (CLU-IN) *United States Environmental Protection Agency - Technology Innovation Office* http://clu-in.com/	Provides information about innovative treatment technologies to the hazardous waste remediation community. It describes programs, organizations, publications and other tools for federal and state personnel, consulting engineers, technology developers and vendors, remediation contractors, researchers, community groups, and individual citizens
International Environmental Technology Center *United Nations Environmental Program* http://www.unep.or.jp/	Provides information on a global scale pertaining to new and innovative sound environmental technologies
Rapid Commercialization Initiative *Federal/State/Private Cooperative effort* http://rci.gnet.org/	Makes use of cooperative demonstration projects to identify barriers to the acceptance and use of new technologies
Superfund *United States Environmental Protection Agency* http://www.epa.gov/superfnd/	Offers a comprehensive data base of CERCLA-related materials including regulatory information, initiatives, programs, and technical information

Technology Demonstrations

One method of overcoming barriers to technology transfer that is gaining popularity, specifically with environmental technology developers, is the use of field-scale technology demonstrations. Research conducted by Griener (1996, 83) supports the use of technology demonstrations to aid in the transfer of environmental remediation technologies. The function of a field-scale demonstration, according to Gierke and Powers (1997: 196), is "to provide information useful for increasing the accuracy of conceptual models of the governing processes and to elucidate the practical aspects of full-scale implementation." Anderson et al. (1992:310) suggest that technology demonstrations determine the overall effectiveness of a particular technology as well as provide a forum to evaluate the potential for implementation and the reliability of the technology. The usefulness of technology demonstrations is apparent when considering the history of pump-and-treat technology, a traditional groundwater remediation technology.

During the 1980s and early 1990s, pumping contaminated groundwater to the surface for treatment was the accepted approach for dealing with contaminated groundwater. During this period, more than 70% of all Superfund site record of decisions included goundwater pump-and-treat technology for addressing groundwater contamination (EPA, 1993:8). Based on a NRC report published in 1997, this number may be as high as 93% (NRC, 1997:35). Figure 2-2 presents Record of Decision data for groundwater contaminated sites between fiscal years 1982 and 1995.

Figure 2-2. Record of Decisions for Groundwater Contaminated Sites Between Fiscal Years 1982 and 1995 (NRC, 1997:35)



Note: *In situ* treatment remedies include: Air Sparging (22); Bioremediation (15); Passive Treatment Wall (3); Dual-Phase Extraction (3); *In situ* Aeration (1); *In situ* Oxidation (1)

Application of this technology has been plagued with difficulty, and cleanup times have been substantially longer than expected to meet regulatory criteria (GAO, 1995b:27). Phenomena limiting the efficiency of groundwater remediation by pump-and-treat technology is now generally understood. However, it was only after observation of the ineffectiveness of many field-scale treatment projects that research was conducted to identify these processes. Conducting comprehensive field-scale demonstrations to evaluate pump-and-treat technology under a range of site-specific conditions could have identified sooner that this technology is often ineffective for reducing groundwater concentrations to regulatory acceptable levels (Gierke and Powers, 1997:197).

In contrast to pump-and-treat technology, the rapid development of bioventing as a method of reducing risk associated with spills of petroleum products illustrates the efficacy of field-scale demonstrations to bring an innovative technology from laboratory-scale to accepted use. This has resulted mainly from a cooperative effort between the Air Force Center for Environmental Excellence (AFCEE), the EPA, and various consulting firms (Gierke, 1997:197). Bioventing field demonstrations were first conducted at Hill AFB in Utah and Tyndall AFB in Florida. These sites represent a large variation in climatic conditions which lead to an increased understanding of technology performance across a spectrum of environmental factors. Integrating the results of field-scale tests with laboratory experiments by Hinchee and Arthur (1991), protocols for field testing the technology at other sites as well for determining remediation cost have been generated. As a direct result of field-scale demonstrations, bioventing technology has been developed to the point where it can be implemented widely (Gierke and Powers, 1997:197).

Anderson et al. (1992:309) suggest three primary considerations related to planning and developing successful technology demonstration programs:

1. Select technologies that have the potential to reduce cost, increase performance, and reduce risk.

2. Work closely with regulatory agencies to gain regulatory and public acceptance.

3. Gather field data on engineering applications related to cost performance, quality and reliability, and the schedule for implementation.

At this point, the objective of this thesis should be reviewed as it relates to the methods of transfer presented thus far. The first research objective presented in Chapter 1 is:

- To identify the barriers to transferring an environmental remediation technology from field evaluation to implementation, as well as the elements necessary to overcome those barriers, in order to apply the technology to remediate DOD contaminated sites.

Many of the methods of technology transfer presented may seem somewhat unrelated to the research objective because they are primarily focused on technology transfer for the purpose of commercialization, rather than implementation at the developing agency (government-developed environmental remediation technologies for implementation at DOD contaminated sites). Note, however, that it is quite unlikely that a government-developed environmental remediation technology could ever be implemented at a DOD contaminated site without transfer, and hence commercialization, to the private sector.

Environmental Remediation Technology Market

During the 1980s, new laws (CERCLA and the 1984 amendments to the Resource Conservation and Recovery Act) increased investor interest in innovative environmental remediation technologies. Investors believed that with such a large number of sites needing cleanup nationwide combined with strict enforcement of the newly passed laws, investments in the environmental remediation technology market would yield high returns. However, after a peak in the commercial market for environmental remediation technologies in 1990, few investments were fruitful. By 1993 the strength of stocks in the environmental remediation technology field had fallen to less than half its peak value, and it has continued to decline. Despite billions of dollars spent on remediation and other

environmental programs annually, companies have struggled to bring new remediation technologies to the market (NRC, 1997:40).

One trend that has emerged over the last decade is that start-up companies founded on trying to market a single innovative remediation technology have generally failed. Table 2-7 shows the recent stock value of seven companies who market an innovative environmental remediation technology. Of the seven companies shown, only one, Thermo Remediation Inc., has not suffered large losses in stock value since the initial public offering. All others have dropped substantially (NRC, 1997:42).

In today's market, environmental remediation technologies are generally provided by large consulting firms offering a diverse range of environmental services rather than by small companies focused on a particular technology or market niche. The one company in Table 2-7 who's stock has not shown substantial losses over its initial offering price, Thermo Remediation, markets a system for treating petroleum contaminated soils but has increasingly diversified its services – it is affiliated with companies that recycle used motor oil, provide wastewater processing services, and remove radioactive contaminants from soils. Additionally, Thermo Remediation acquired Remediation Technologies Inc., an engineering/environmental firm that provides a range of environmental services (NRC, 1997:42).

Table 2-7. Stock Value of Selected Technology Companies (After NRC, 1997:43)

COMPANY	TECHNOLOGY AREA	Initial Public Offering		RECENT SHARE PRICE
		DATE	SHARE PRICE	
Envirogen	Biotreatment applications	August 1992	$7.00	$2.75 *(19 Nov 96)* $2.88 *(3 Sep 97)*
Molten Metal Technology	Catalytic extraction Processes	February 1993	$16.00	$15.00 *(19 Nov 96)* $5.31 *(3 Sep 97)*
Ensys Environmental Products	Immunoassay products	October 1993	$10.00	$1.50 *(19 Nov 96)* NLS *(3 Sep 97)*
Purus Inc.	VOC control	November 1993	$14.00	$4.38 *(19 Nov 96)* $3.63 *(3 Sep 97)*
Thermo Remediation Inc.	Thermal processing	December 1993	$8.00	$10.00 *(19 Nov 96)* $7.13 *(3 Sep 97)*
Conversion Technologies International	Vitrification technology	May 1996	$4.50	$2.00 *(19 Nov 96)* $1.75 *(3 Sep 97)*
Thermatrix	Flameless thermal oxidation	June 1996	$12.50	$9.75 *(19 Nov 96)* $2.50 *(3 Sep 97)*

Note: Initial public offering prices for the first five companies are quoted to the nearest point. Recent share prices as of 19 Nov 96 are values published in the source document. 3 Sep 97 values have been added.
NLS = No Longer Solvent (Stock in this company is no longer offered)

While research continues to develop innovative solutions to environmental problems, few small firms founded on new research ideas have been able to survive in the environmental remediation technology field. The inability of small firms to survive discourages innovation. The large-scale service oriented firms generally provide their clients with traditional technologies rather than risking a new approach that might perform better than the traditional one but also has a larger chance of failing. This trend is making it increasingly harder to overcome the barriers to environmental remediation technology transfer (NRC, 1997:42).

Barriers to Technology Transfer

Many authors offer consolidated lists of barriers to technology transfer in a general sense (Baron, 1990; Carr, 1992). Gary G. Broetzman, however, provides a discussion of barriers specific to the transfer of innovative environmental remediation technologies. Broetzman suggests that the transfer and use of innovative cleanup methods has been stifled by (1) the lack of cost and performance data, and (2) an inflexible institutional/regulatory framework (Broetzman, 1997:324). Basing his work on research conducted by the Colorado Center for Environmental Management (Colorado Center for Environmental Management, 1993), barriers identified by Broetzman that are directly associated with uncertain performance of an innovative environmental remediation technology include risk aversion, a desire to expedite cleanup, and a desire to maintain a projected budget.

Risk Aversion

Environmental regulators play an important role in the acceptance and use of an innovative technology. They are accountable to both their management and the public when assuming risks. Often, regulators are unwilling to assume the risk of an innovative cleanup technology that may not prove to be safe or effective (Broetzman, 1997:324). Griener (1996:82) also indicates that regulatory oversight presents barriers specific to the transfer of environmental remediation technologies. Unlike the development of many other technologies, environmental remediation technologies must be proven to work before regulators overseeing site cleanups will consider use of the technology (Griener, 1996:82).

Desire to Expedite Cleanup

Those involved with the remediation of a contaminated site have an incentive to expedite cleanup. Remedial site managers and regulators must adhere to scheduled milestones and those not directly involved in the cleanup, the general public, favor quick action (Broetzman, 1997:324). Although the use of an innovative technology can often expedite cleanup, selecting an innovative technology and gaining the necessary approval of the site regulator can be more time consuming than implementing a traditional technology.

Desire to Maintain Projected Budget

Responsible parties have financial incentives to minimize cleanup costs and site managers are under pressure to maintain projected budgets. The use of an innovative technology may drive up costs in the short-term and may exceed budgets if the technology DOEs not perform as expected (Broetzman, 1997:324).

Specific institutional barriers that may impede the implementation of an innovative technology include regulatory standards, and permitting procedures (Broetzman, 1997:324).

Regulatory Standards

Regulatory standards can often impede, rather than facilitate, the use of an innovative technology to remediate a contaminated site (Broetzman, 1997:324). For example, *in situ* bioremediation technologies often require injection of substances into the subsurface.

Regulatory standards may preclude this, thereby inhibiting use of an innovative technology.

Permitting Procedures

Permitting of innovative technologies is often a lengthy procedure and may not be familiar to regulators. In addition, interagency friction may develop when one agency is ready to approve the use of an innovative technology while another agency insists on adhering to permitting processes used for traditional technologies (Broetzman, 1997:324).

Griener (1996) evaluated the transfer of general environmental technologies. One environmental remediation technology reviewed in his work that has been successfully transferred is bioventing. Four barriers to the transfer of this technology were found: regulatory agency oversight, lack of awareness of new technology, difficulty in clearly defining the end-user, and task saturated personnel (personnel tasked to the degree that they are overwhelmed) (Griener, 1996:75). Of these, Griener suggests that regulatory agency oversight and difficulty in clearly defining end-user are technology transfer barriers specific to the transfer of environmental technologies. Regulatory agency oversight is a barrier because frequently environmental technologies are developed to "counter environmental regulations and policy that the user must comply with" (Griener, 1996:82). Difficulty in clearly defining the end-user stems from the idea that there is not a single user of an environmental remediation technology (Griener, 1996:82). Most general technologies are developed to be used in conjunction with a specific machine or

process making the end-user obvious. Environmental remediation technologies may be used by many different organizations making the end-user somewhat difficult to define.

A recently published NRC report provides further insight into the regulatory barriers impeding the transfer of environmental remediation technology. In it, the enforcement and execution of CERCLA is identified as one of the main barriers to innovative technologies achieving commercial implementation. For example, although regulations established for technology selection are strictly enforced, penalties for failing to initiate remediation promptly are minimal. In many instances, it is less costly for site owners to delay cleanup through litigation rather than select a technology and begin cleanup (NRC, 1997:45). It has been shown that the average cost to clean up a private-sector CERCLA site is $24.7 million (CBO, 1994). However, analysis conducted by NRC of corporate reports and financial statements indicates that companies report, on average, a liability of $1 million annually for sites where cleanup has not yet started (NRC, 1997:45). Many companies are therefore faced with a decision to either forego immediate cleanup and carry a $1 million dollar annual expenditure to delay cleanup or to immediately expend nearly $25 million in cleanup –a major portion, or possibly all, of its cash revenues. Faced with this situation, there is little debate that delay is the preferred alternative.

Regulatory restrictions also limit the ability of a site owner to change cleanup remedies midway through a cleanup. Since currently accepted environmental remediation technologies are expensive, site owners have little incentive to begin immediate cleanup. Those that do initiate cleanup and wish to switch to a new technology that may be less

costly are faced with bureaucratically cumbersome mechanisms for remedy change (NRC, 1997:45). Again, delay is encouraged.

Adding to the incentive to delay cleanup is the possibility that regulatory levels defining "how clean is clean" may change. Current political pressure for CERCLA reform is tending toward less stringent cleanup standards and requiring cleanup at a narrower range of sites (NRC, 1997:45). If companies and government agencies knew for certain that existing cleanup standards would be strictly enforced, there would be an incentive to remediate contaminated sites sooner. In addition to changing regulation, there is often disagreement among regulatory agencies as to the interpretation of existing regulation. The NRC reports that soil cleanup goals for polycyclic aromatic hydrocarbons at 14 CERCLA sites ranged from 0.19 to 700 parts per million (NRC, 1997:50). Although the variation was a function of what decision regulators made about the future use of the site, factors weighed in making the decision were unclear. For example, cleanup standards varied among sites that were equally near to residential areas (NRC, 1997:50). Current regulations allow for wide discretion by regulators about the level of cleanup required at a given site and different regulators may employ different methods to reach decisions about cleanup levels. Without clear, consistent regulatory requirements, it is difficult for technology developers to prove to potential customers that their technology is acceptable to regulators, even if the developer has reliable cost and performance data.

Barriers to the transfer of an innovative environmental remediation technology do not exist exclusively in the private sector. A 1995 GAO report comments on a barrier specific to the public sector –inadequate cost containment (GAO, 1995b:3). Inadequate

cost containment has decreased the incentive for federal remediation contractors to select an innovative technology. Because most remediation contracts are awarded on a cost-reimbursable basis, there is little incentive for cost effectiveness. According to the GAO audit, cost overruns are common to remediation efforts at government sites, due in part to inadequate oversight of contractors (GAO, 1995b:3). GAO found evidence of fraud waste and abuse by federal remediation contractors (GAO, 1995b:5). With little incentive to reduce costs, there is no incentive for federal remediation contractors to search for innovative, cost-effective, technologies.

Environmental Remediation Technology Transfer Initiatives

With the goal of overcoming technology transfer barriers, there have been a number of initiatives focusing on the transfer of environmental remediation technology. Many of these initiatives involve partnerships between government agencies and private groups. The initiatives can be grouped according to those that fund and sponsor technology demonstrations, and those that focus on information dissemination in order to facilitate technology transfer. An overview of the most notable initiatives follows.

The first group of initiatives to be reviewed engage in technology demonstrations. Research conducted by Griener (1996:65) supports the use of demonstration and testing to aid in the transfer of environmental remediation technologies. Most of these initiatives focus on compiling cost and performance data that accurately describes the technology under evaluation. Some of these initiatives include certification programs for technologies that are demonstrated to perform well.

Environmental Security Technology Certification Program (ESTCP)

Headed by DOD, ESTCP's goal is to demonstrate and validate promising, innovative technologies that target DOD's most urgent environmental needs. The purpose of the program is to provide DOD with a return on investment through cost savings and improved remediation efficiency. ESTCP's strategy is to select technologies that have performed well in laboratory studies and have DOD and commercial applications. Then, with involvement of DOD end-users and the regulatory community, ESTCP demonstrates the technology at field-scale to document cost, performance, and market potential. By involving DOD end-users, environmental remediation technologies with successful field-scale demonstrations, leading to ESTCP certification, have a higher potential for complete technology transfer and implementation at a DOD-owned contaminated site (ESTCP, 1997:1).

Environmental Technology Verification Program (ETV)

Managed as part of the President's Environmental Technology Initiative by EPA's Office of Research and Development, ETV was created to accelerate the entrance of new environmental technologies (including environmental remediation technologies) into public and private sector use. ETV verifies the performance of innovative technologies and supplies technology buyers, technology developers, consulting engineers, states, and EPA regions with high quality data on the performance of new technologies. ETV projects draw on the experience of "partner organizations" to design efficient processes for conducting tests of new technologies with EPA oversight. Partners are selected from both the public and private sectors, including federal laboratories, states, universities, and

private sector facilities, to perform and report verification activities based on testing and quality assurance protocols developed with input from all major stakeholders (EPA, 1997b:1). Canada has developed a similar program under the same name, Environmental Technology Verification program. The program goals are quite similar to those of the U.S. program. Canada and EPA are currently working together to develop reciprocity agreements between the verification programs (Canada Verifies, 1997).

Rapid Commercialization Initiative (RCI)

Although this initiative involves DOD, DOE, and EPA, it is headed by the Department of Commerce. RCI is based on a program started in 1994 by the California Environmental Protection Agency to certify technologies designed for hazardous waste treatment. The initiative provides certification of environmental remediation technologies after independent performance and cost evaluation. Although users selecting technologies that have been certified through RCI still have to adhere to established environmental law, obtaining necessary permits for technology use is somewhat easier (Parkinson, 1995:34).

Remediation Technologies Development Forum (RTDF)

Established in 1992, RTDF is the result of a meeting between industry representatives and EPA's Administrator aimed at identifying ways to work together to solve complex remediation problems. RTDF is designed to foster public-private partnerships to develop, test, and evaluate innovative environmental remediation technologies. RTDF is composed of partners from industry (47%), government agencies (32%), and academia

(21%). Additionally, RTDF addresses scientific, institutional, and regulatory barriers to innovative environmental remediation technologies (RTDF, 1997:1-2).

Strategic Environmental Research and Development Program (SERDP)

Headed by DOD, with involvement of DOE and EPA, among other activities SERDP maintains six tests centers dedicated to testing technologies for specific classes of wastes. Generally, the Air Force works with dense, non-aqueous phase liquids (including chlorinated solvents) in groundwater; the Navy is doing applied research and demonstration of *ex situ* and *in situ* remediation technologies for fuel hydrocarbons; the Army is concerned with soils, sediments and groundwater contaminated by explosives or heavy metals; and EPA works with combined organics. The purpose of this program is not only to evaluate new technologies, but also to standardize data collection, particularly for cost and performance. This standardization allows for easier comparisons of alternative technologies (Parkinson, 1995:33).

Superfund Innovative Technology Evaluation (SITE)

Authorized by the Superfund Amendments and Reauthorization Act of 1986, SITE is administered by the EPA Office of Research and Development. The purpose of SITE is to "accelerate the development and use of innovative cleanup technologies applicable to Superfund and other hazardous waste sites." SITE accomplishes this purpose through technology demonstrations designed to provide performance and cost data on selected technologies. For each technology evaluated under the SITE initiative, EPA publishes an innovative technology report which is available to the public (EPA, 1995b:iii).

The second set of initiatives do not engage in technology demonstrations. Instead, these initiatives compile data from demonstrations and case studies and make the data available to the environmental community through information dissemination mechanisms such as reports, mailings, and the internet.

Federal Remediation Technologies Roundtable (FRTR)

FRTR is comprised of EPA, DOD, DOE, the Department of the Interior, the National Aeronautics and Space Administration, Tennessee Valley Authority, and the Coast Guard. The initiative was created to exchange information on site remediation technologies, and to consider cooperative efforts that could lead to a greater application of innovative environmental remediation technologies. The Roundtable publishes case studies of remediation projects to document the results and lessons learned from technology applications. These publications help establish standards for cost and performance data which should lead to greater confidence in the selection and use of innovative cleanup technologies (FRTR, 1995b:ii).

Ground-Water Remediation Technologies Analysis Center (GWRTAC)

Established in 1995, GWRTAC is operated by the National Environmental Technologies Applications Center (NETAC), in association with the University of Pittsburg's Environmental Engineering Program, under a cooperative agreement with the EPA Technology Innovation Office. GWRTAC compiles, evaluates, and distributes information on innovative groundwater remediation technologies. GWRTAC prepares reports by technical teams selectively chosen from NETAC, the University of Pittsburgh,

and other supporting institutions. In order to ensure that GWRTAC meets the needs of a diverse goundwater remediation community, its activities are guided by an external committee composed of representatives from interested public and private sector organizations (GWRTAC, 1997:1).

Interstate Technology and Regulatory Cooperation (ITRC)

Initiated in 1994 as a subcommittee of the DOE-sponsored Demonstration of On-Site Technologies effort, ITRC is composed of 22 states and several federal agency representatives. The mission of ITRC is to "facilitate cooperation among the states in the implementation of innovative technologies that will clean up contaminated sites safely, economically, effectively, and quickly" (Broetzman, 1997:323). ITRC conducts innovative technology studies, staffed by members from various states. The primary goal of the studies are to document and report how state regulatory agencies encourage use of innovative technologies for environmental cleanup. Similar to the intent of this thesis, ITRC focuses on emphasizing approaches to resolving barriers rather than focusing on the barriers themselves (Broetzman, 1997:323). ITRC released its first guidance documents for state regulators in June, 1996 (Cooney, 1996:432).

National Technology Transfer Center (NTTC)

Established in 1992, NTTC is located at Wheeling Jesuit College, and is administered by NASA. NTTC maintains a database of government technologies for the benefit of industry. Of relevance to this thesis is the environmental division of NTTC. This division researches site specific characteristics of a particular contaminated site and, after

searching the NTTC database, offers potential environmental technology alternatives. This initiative hopes to aid in the implementation of new technologies by providing an avenue for site owners to become educated about innovative technologies that may be appropriate for their particular site (Parkinson, 1995:34).

TechDirect

Administered by the EPA Technology Innovation Office, TechDirect is an electronic service with the purpose of disseminating information about developments in technologies for site characterization and remediation. The initiative provides a monthly electronic mailing to interested parties describing the availability of recent relevant publications or upcoming events, such as conferences, and directs the recipient to the appropriate place to obtain further information (TIO, 1997).

Vendor Information System for Innovative Treatment Technologies (VISITT)

VISITT is a PC-based program developed by EPA that contains data on innovative environmental remediation technologies. Released in December 1996, VISITT version 5.0 has a database containing 346 technologies. VISITT works with a "keyword" search. Each search is based on user specified preferences including contaminant type and site conditions. The advantage of VISITT over traditional electronic search engines is that it standardizes the search process by using consistent terminology for the keywords. Information provided by VISITT, based on a search, includes technology summaries, vendor information, project specific costs, and performance data (Gierke and Powers, 1997:197). The software is designed to make it easier for technology users to discover

innovative technologies that may be appropriate for cleanup of their contaminated site. VISITT is public domain and can be downloaded from the internet at the Hazardous Waste Clean Up Information (CLU-IN) site referenced in Table 2-4.

Remediation Options (ReOpt™)

ReOpt™ version 2.1 is an initiative similar to VISITT and is available in both PC and Macintosh versions. ReOpt™ contains 107 technologies (at the time this thesis was written) and, in addition to the same data that is provided by VISITT, lists regulatory constraints particular to each technology (Gierke and Powers, 1997:197).

Innovative Treatment Technologies Database

Like VISITT and ReOpt™, version 2.0 of Innovative Treatment Technologies Database uses a keyword search engine to search innovative treatment technology data. Released in 1996, the database contains information on planned, ongoing, and completed applications of innovative treatment technologies at CERCLA and other sites. The database provides information on 345 innovative projects at CERCLA sites, 10 projects at RCRA corrective action sites, 33 projects at removal sites, and 33 projects at non-NPL federal agency sites (TechDirect, 1997).

Technology Transfer Legislation

In addition to the initiatives to overcome barriers to technology transfer described above, legislation has also been introduced to enhance technology implementation. Although the

legislation was not specifically introduced for environmental remediation technologies, it is quite applicable.

The Stevenson-Wydler Technology Innovation Act of 1980 (Public Law 96-480) required all federal agencies conducting research and development to include technology transfer in their mission. It also required agencies to establish an Office of Research and Technology Applications to identify technologies and ideas with potential applications in other settings. For example, research on microorganisms used to degrade environmental contaminants could possibly be used to understand human health hazards posed by microbial viruses. In order to spur technology transfer, the Bayh-Dole Act of 1980 (Public Law 96-517) permitted government-owned laboratories to grant exclusive licenses and permitted universities, nonprofits, and small businesses to obtain title to inventions developed with government support. The Federal Technology Transfer Act (FTTA) of 1986 (Public Law 99-502) amended the Stevenson-Wydler Act and authorized government-owned, government-operated laboratory directors to enter into Cooperative Research and Development Agreements (CRDA) with the private sector. A CRDA is an agreement that provides a written and legal framework for collaborative efforts between federal laboratories and private sector cooperators. CRDAs are one of the primary mechanisms through which collaboration between the government and private sector takes place under the FTTA. The CRDA could contain advance agreements on the title and license to inventions resulting from the research conducted under the cooperative agreement. FTTA also required that a significant portion of license royalties be paid to federal laboratories and their employee inventors whether the invention came out of a

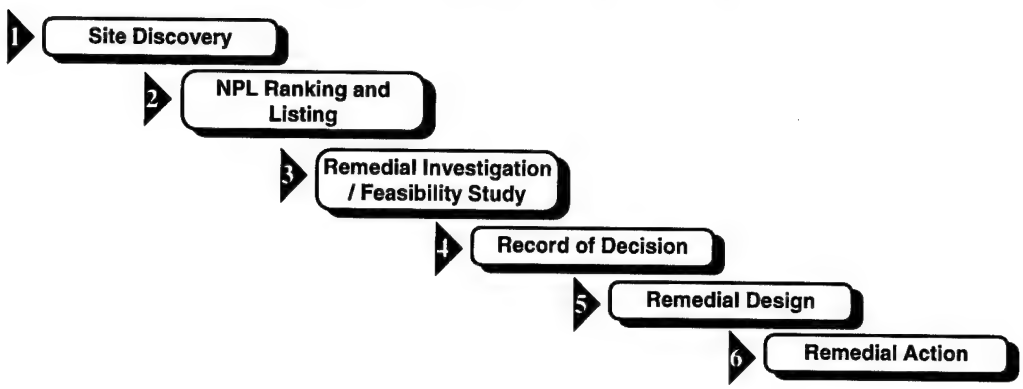
CRDA or was licensed using the procedures of the Bayh-Dole Act. The FTTA also promotes collaboration between federal agencies and government-operated laboratories and other government and non-government entities. Executive Order 12591 (10 April 87) as amended by executive order 12618 (22 Dec 87) reiterates the purpose and goals of the FTTA (Gatchett, 1992:893). The National Competitiveness Technology Transfer Act (NCTTA) of 1989 (Public Law 101-189) amended FTTA and made technology transfer a mission of government-owned, contractor-operated (GOCO) laboratories and their employees. Under NCTTA, CRDAs were authorized for GOCO laboratories (DOE, 1997:9).

CERCLA Performance Evaluation Criteria

Although legislation is in place to facilitate the transfer of environmental remediation technology and full-scale demonstrations are being conducted pursuant to the same goal, there is a critical factor that must be considered before there is even a possibility that an environmental remediation technology will be successfully transferred and, more importantly, implemented: the CERCLA performance evaluation criteria. Under CERCLA, EPA has developed a systematic set of performance evaluation criteria for use by site managers when selecting a remediation technology. The criteria are derived from requirements found in the National Contingency Plan (40 CFR 300) and CERCLA sections 121(b) and 121(c). The criteria are designed to provide structure to the technology selection process and to capture the full range of performance issues associated with an environmental site remediation project (Skumanich, 1994:415).

During a site remediation project, EPA uses a six-step remedial process. This process is shown in Figure 2-3 (Masters, 1991:190).

Figure 2-3. CERCLA Remedial Process



During the remedial investigation / feasibility study step of the CERCLA remedial process, information used to evaluate the usefulness of different environmental remediation technologies is gathered. Then, by applying the CERCLA performance criteria, an assessment is made as to how well each viable technology will perform at the particular site under investigation and is recorded in the Record of Decision (ROD). The technology determined to be the most appropriate for the site is also recorded in the ROD along with a detailed explanation of the selection (Skumanich, 1994:415).

The nine performance criteria identified by EPA used to select an environmental remediation technology are shown in Table 2-8.

Table 2-8. CERCLA Technology Performance Criteria

1. Overall protection of human health and the environment
2. Compliance with all other applicable or relevant and appropriate requirements (ARARs)
3. Long-term effectiveness and permanence
4. Reduction of toxicity, mobility, or volume through treatment
5. Short-term effectiveness
6. Implementability
7. Cost
8. State acceptance
9. Community acceptance

The first two criteria are threshold criteria. Any technology selected for use at a particular site must fully satisfy these criteria to be acceptable.

Overall Protection of Human Health and the Environment

Although listed first by the EPA, this criterion is actually used as a final assessment to determine whether the technology will function in a safe manner that will provide adequate protection to human health and the environment. It therefore is closely related to other criteria, especially long-term effectiveness and permanence, short-term effectiveness, and compliance with ARARs. Because of this relationship, a technology that is assessed to perform well relative to the other criteria should be able to satisfy this encompassing criterion of overall protection of human health and the environment.

Compliance with ARARs

This criterion is used to determine how well a proposed environmental remediation technology complies with federal, state, and local environmental laws. This criterion has the objective of ensuring that no other environmental requirements are violated during a remediation project.

The next five CERCLA performance criteria are balancing criteria. The performance of a remediation technology DOEs not have to fully satisfy each of these criteria. Instead, the criteria are used as overall performance indicators, meaning that the selected technology must demonstrate the best overall performance relative to these criteria (Skumanich, 1994:416).

Long-Term Effectiveness and Permanence

This criterion is used to evaluate the ability of a proposed environmental remediation technology to reliably protect human health and the environment, after the cleanup is completed. Relevant to this criterion are how permanent and complete the cleanup will be and what risks will be presented by remaining contamination at the site. Additionally, the criterion evaluates what kinds of long-term controls will be needed at the site to manage any residual contamination. EPA has generally favored permanent treatment technologies (destruction) over technologies that pose the possibility of contaminants being re-released to the environment (containment). EPA also favors technologies that treat contaminants at the site rather that those that require removal to off-site locations (Skumanich, 1994:418).

Reduction of Toxicity, Mobility, and Volume through Treatment

The objective of this criterion is to measure the degree to which the proposed remediation technology includes direct treatment of the contamination, as opposed to containment or disposal elsewhere. This criterion presents some obvious overlap with the preceding long-term effectiveness and permanence criterion. However, the focus here is more specifically on the changes to the particular contaminants, including how much hazardous material will be destroyed, what reductions in toxicity, mobility, or volume will occur, and what type and quantity of treatment residuals will be created. This criterion favors technologies providing irreversible treatments that reduce the toxicity, mobility, or volume of contaminants (Skumanich, 1994:418).

Short-Term Effectiveness

This criterion is used to measure the risks posed to workers, the community, and the environment during the construction and implementation phases of the site remediation. Under this criterion, technologies favored are those that require a relatively short and uncomplicated construction period and a relatively short time to implement. Additionally, those technologies that pose the least disruption to the environment are preferred as are those whose impacts to the environment can be easily monitored. EPA traditionally rejects the selection of an environmental remediation technology that poses a significantly high short-term risk to workers (Skumanich, 1994:419).

Implementability

The objective of this criterion is to measure the technical and administrative feasibility of a proposed remedy. This includes consideration of the availability of required materials and services. This criterion favors environmental remediation technologies that are implemented with little difficulty. Generally, how well documented the performance of remediation technology is will determine how well a technology is evaluated in relation to this category (Skumanich, 1994:419).

Cost

Under this criterion, present-values are calculated for all relevant costs over the multiyear period of the cleanup project. The objective of this criterion is to identify technologies that pose reasonable costs, not necessarily the technology with the lowest cost. As long as a technology is shown to be reasonable in cost relative to its remedial effectiveness, it may be selected over a technology that costs less overall. EPA is careful to make this distinction because of other important factors, such as cleanup time, that may be more critical to a decision than cost (Skumanich, 1994:420).

The final two criteria are modifying criteria. The purpose of modifying criteria is to ensure that state and local concerns not directly addressed in the threshold and balancing criteria are given adequate attention. Modifying criteria tend to deal with issues similar to those addressed in other areas of the performance criteria, though state and local concerns may deal with specific issues not otherwise addressed.

State Acceptance

This criterion is used to assess the degree to which the remedy addresses any policy or administrative issues that the state may have. This criterion DOEs not address issues relating specifically to meeting state laws , as they are covered in the ARAR criterion.

Community Acceptance

This criterion is used to measure the acceptance of a proposed remedy by the local community. During this step in the CERCLA performance evaluation, the public is given the opportunity to submit comments on the various environmental remediation technologies evaluated. Only after public comment can the final selection of a technology to remediate a particular site be made and recorded in the ROD (Skumanich, 1994:421).

When selecting a technology to be used at a particular site, site managers generally do not use a rigorous or quantifiable method to balance the technologie's ability to satisfy the CERCLA performance criteria. To be considered, a technology must clearly meet the two threshold criteria and be shown to perform adequately relative to the balancing and modifying criteria. Determination of a site remedy is largely based on the judgment of the site manager. In some instances, five-point or other numeric rating scales may be used to summarize the performance of the technology relative to each of the criteria, but the ultimate determination is largely based on the site manager's professional judgement (Skumanich, 1994:421).

The implementation of an innovative technology depends heavily on its ability to perform well when evaluated against the CERCLA performance criteria. An innovative technology which is not competitive with a "traditional" one, when evaluated using the CERCLA criteria, will likely not be implemented.

Conclusion

Technology transfer is a complex thing. Rules established for one organization or specific type of technology seldom hold true for other organizations or related technologies. Regulations, attitudes, and budgetary constraints are just a few of the many parameters that interact to determine the ultimate success or failure of the transfer of technology. Some conventional wisdom about technology transfer offered by Robert Carr concludes that:

> *Barriers to technlogy transfer are mostly man-made (organizational resistance, laws and regulations, etc.). It requires persistent, vigorous activity by men and women to overcome them.* (Carr, 1992b:33)

We shall try, in this thesis, to provide insight on how technology in one focused area, environmental remediation, can be effectively transferred from demonstration to commercialization.

In order to provide insight to the transfer of environmental remediation technologies, a methodology capable of exploring the many issues relevant to the transfer of environmental remediation technology transfer must be employed. For this purpose, a qualitative methodology, convergence methodology, is selected and reviewed in the

following chapter. This methodology is exploratory in nature, allowing relevant topics to be thoroughly reviewed.

III. Methodology

Introduction

The purpose of this chapter is to define the method by which this research shall be conducted. Since peer reviewed literature focused on the topic of environmental remediation technology transfer is minimal, this effort is primarily one of exploration, or what Dane terms *descriptive research* (Dane, 1990:6). According to Dane, "descriptive research involves the examination of a phenomenon to more fully define it or to differentiate it from other phenomena" (Dane, 1990:6). The phenomenon to be defined is the process of environmental remediation technology transfer from full-scale demonstration to implementation. Furthermore, our goal will be to differentiate it from generalized technology transfer, which has already been researched extensively. Since this thesis is one of only a handful of studies focused on the transfer of environmental remediation technology, it is overly ambitious to hope that all of the parameters relevant to the transfer of an environmental remediation technology will be exposed and fully characterized within this single effort. A topic in its infancy, such as this, must undergo an evolutionary series of studies before full disclosure can be realized. However, through the preparation and execution of solid methodology, we hope to identify the majority of factors relevant to environmental remediation technology transfer.

Descriptive research demands the use of qualitative, rather than quantitative methods. This chapter presents a brief overview of the utility of qualitative research as compared to quantitative research as they relate to the topic of environmental remediation technology

transfer. Following this discussion, the methodology used in this research, *convergent methodology*, will be presented.

Qualitative and Quantitative Approaches to Research

In *Qualitative Evaluation and Research Methods*, Patton (1990) offers a fine overview of the strengths and weaknesses of qualitative and quantitative research approaches. Patton's comments are particularly applicable to this thesis because although quantitative methods are traditionally associated with technical studies, Patton focuses on the use of quantitative methods to study the actions and interactions of people. Patton suggests that quantitative methods require the use of standardized measures so that the varying perspectives and experiences of those being evaluated can be placed in predetermined response categories to which rankings are assigned (Patton, 1990:14). The advantage of quantitative methods is that it is possible to measure the response of a great number of people to a relatively small number of questions, facilitating the use of statistical aggregation of the data. This results in a broad, generalized set of conclusions. Conversely, the use of qualitative methods gives the researcher the freedom to explore selected issues in depth and detail. Qualitative methods approach fieldwork without the constraint of predetermined response categories (Patton, 1990:13). This typically produces a wealth of detailed information about a much smaller number of people or situations, increasing the understanding of the cases and interactions relevant to the topic under evaluation, but reducing generalizability (Patton 1990:14).

Exploratory research, such as this, requires use of interviews as at least one method of gathering relevant data (Wright, 1979:51). Although the groups to be interviewed, technology developers, technology users, consultants, and environmental regulators, were predetermined, the sample size of each primary group was unknown at the time this methodology was selected. A method that did not require a large sample population, such as qualitative methods, was preferred over that of a method requiring a massive sample size. Furthermore, as indicated in the introduction to this chapter, the focus of this thesis is to move away from the topic of generalized technology transfer and move toward technology transfer specific to environmental remediation technology. Qualitative methods support each of these goals.

Patton (1979:10) indicates that there are three categories of data collection in qualitative methods:

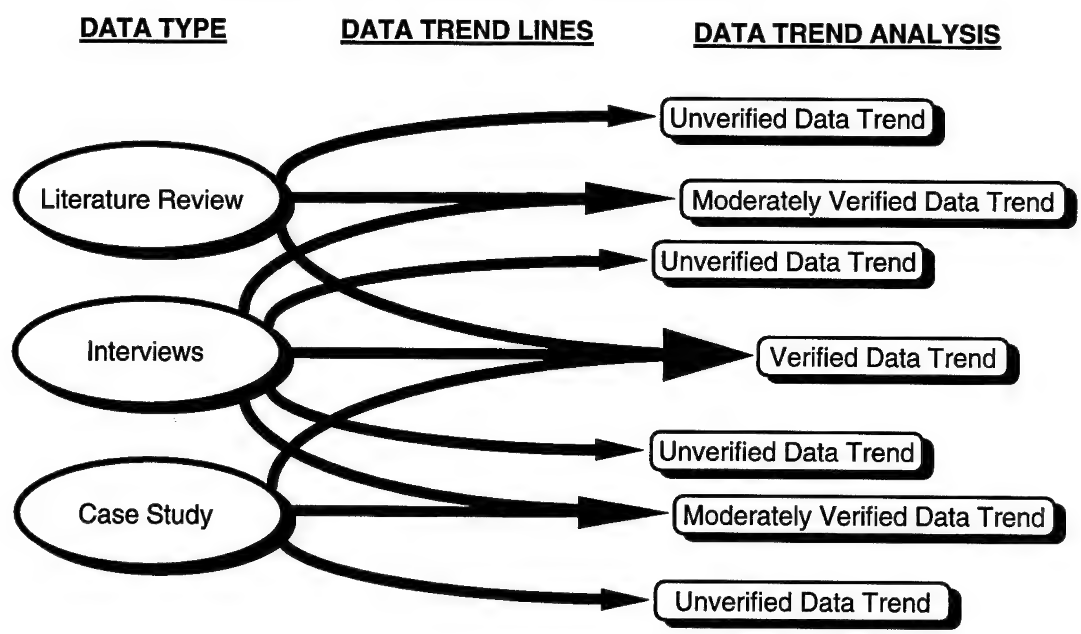
1) In-depth, open-ended interviews
2) Direct observation
3) Written documents

Convergent methodology, the methodology selected for this research, will be the tool used to combine each of these categories of data collection into a single useful form, capable of exposing factors important to the transfer of an environmental remediation technology.

Convergent Methodology

Convergent methodology, a term first used by Campbell (1959), makes use of multiple methodologies or data sources in the study of the same phenomena. Convergent methodology focuses on trends or ideas that emerge from the individual data sources and seem to converge on a common phenomena. As presented earlier, the sources of data utilized in this effort are interview, document review/literature review, and direct observation/case study. Figure 3-1 depicts the methodology to be employed.

Figure 3-1. Convergence Methodology



An important way to strengthen any study is through the use of multiple methodologies (Patton, 1990:187). Shown in Figure 3-1, through the use of multiple methodologies, data trends can lead to what we shall call unverified data trends, moderately verified data trends, or verified data trends. A data trend is simply a phenomena or idea that emerges

through review of one or more of the data sources. For example, a trend revealed through the literature review presented in Chapter 2 is that full-scale demonstrations may be appropriate to overcome some technology transfer barriers. An unverified data trend is a trend demonstrated through one source of data that is not observed in any of the other data sources. This does not mean that the trend does not exist, merely that it is not a strong enough trend to be realized in the other data pools. For example, unless the use of full-scale demonstrations to overcome some technology transfer barriers is a trend revealed through interviews, the technology case study, or both, this trend will remain an unverified data trend. A moderately verified data trend is one which has some verification by another source of data, but not all sources of data verify the trend. For example, if the use of full-scale demonstrations to overcome some technology transfer barriers is revealed through one of the other data sources in addition to the literature review, the trend will be declared a moderately verified data trend. When all sources of data clearly converge in support of a data trend, we shall describe that trend as verified.

Use of multiple data sources in a qualitative study helps to validate the findings of the study. Studies that hope to provide accurate conclusions which rely on only one source of data are more vulnerable to errors linked to the particular method used to gather that data (Patton, 1990:188). For example, a research effort relying completely on interview strategies runs the risk of reporting inaccurate findings due to the possibility of loaded interview questions, or biased or untrue responses. Bouchard (1976:268) suggests that the convergence or agreement between two methods "… enhances our belief that the results are valid and not a methodological artifact" (Bouchard, 1976:268). For this

reason, studies that provide cross-data validity checks, such as convergent methodology, are preferred (Patton, 1990:188).

The convergent methodology is designed to identify those trends that seem to converge when reviewing multiple data sources. However, Jick (1983:143) contends that divergent trends may also be relevant. When different measures yield dissimilar results, the researcher is motivated to reconcile the difference. In seeking explanations for divergent results, the researcher may actually be led to unexpected results or unseen factors, giving depth to the research findings. Therefore, the multi-method approach to qualitative research is useful whether there is convergence or not. Where there is convergence, confidence in the results grows considerably. When divergent results emerge, alternative, and likely more complex, explanations are revealed.

In this study, literature review data, case study data, and interview data shall be the sources of data compiled for application of the convergent methodology.

Literature Review Data

Chapter 2 is a review of technology transfer literature. In that chapter, literature directly applicable to the transfer of an environmental remediation technology is presented. The review offers some trends that require validation by the other data sources. For example, the literature review revealed methods of technology transfer that centered on the use of patenting procedures. However, little literature directly supporting the use of patents for the transfer of environmental remediation technology was discovered. Because the use of

patents to transfer environmental remediation technologies has not yet been verified by other data sources to have utility, the trend is currently unverified. Furthermore, some of the barriers identified in Chapter 2 were barriers of technology transfer not specific to environmental remediation technology and they too require validation by other data compilation methods.

Patton (1990:163) indicates that the review of relevant literature can help focus a study while providing a source of data. He warns, however, that the execution of a literature review prior to other qualitative data gathering can "bias the researcher's thinking and reduce openness to whatever emerges in the field." With this in mind, the use of convergent methodology is again supported because it can guard against this pitfall by requiring validation of trends by other data sources.

Case Study Data

Case studies are useful when the goal of a researcher is "...to understand some special people, particular problem, or unique situation in great depth..." (Patton, 1990:54). Since the focus of this thesis is on a particular problem/unique situation, the transfer of environmental remediation technology from full-scale demonstration to implementation, the use of a case study is clearly justified.

A technology that is appropriate for the case study is In-Well Air Stripping, commercially known as NoVOCs. NoVOCs is an environmental remediation technology that has been successfully transferred from full-scale demonstration to implementation. A detailed

review of the evolution of NoVOCs from the technology concept to implementation will serve as a source of data revealing appropriate, as well as inappropriate, actions to take when transferring an environmental remediation technology. Chapter 4 focuses on NoVOCs technology.

Also a second case study is to be presented, *in situ* aerobic cometabolic bioremediation. This case study can be found at Appendix C. Unlike NoVOCs, this technology has not been transferred and commercialized but rather, it is somewhere on the technology transfer continuum, having completed, only recently at the time this is written, a full-scale demonstration. While the review of *in situ* aerobic cometabolic bioremediation does provide a means of understanding the technology transfer process, it is not introduced as a source of data expected to reveal environmental remediation technology transfer characteristics. Rather, its inclusion in this thesis is for the purpose of demonstrating the application of the results and conclusions of this research to an innovative environmental remediation technology. Future research may evaluate the degree of success which recommendations made in this thesis had in the transfer if *in situ* aerobic cometabolic bioremediation.

Interview Data

Of the three sources of data available to research the topic of environmental remediation technology transfer, the method expected to provide the most useful data is interviewing. This is because the interview process will directly involve those most intimate with environmental remediation technology transfer: technology developers, technology users,

consultants and environmental regulators. Although there are many documented types of interview strategies, the interview strategy selected for use in this research is what Patton (1990:281) terms the *informal conversational interview.*

Informal Conversational Interview

The informal conversational interview is the most open-ended approach to interviewing. The conversational interviewer wants to maintain maximum flexibility to be able to pursue information in whatever direction appears to be appropriate, depending on particular responses of the interviewee. No predetermined rigid set of questions is possible in this form of interviewing because the interviewer does not know before the interview takes place which direction the conversation will lead and thus what will be important to ask. Rather, a general set of topics for discussion based on the interview category (technology developer, technology user, or environmental regulator) is preferred (Patton, 1990:282).

Patton (1990:283) suggests the use of an *interview guide* for conversational interviewing. An interview guide is a list of questions or topics that are to be explored in the course of the interview. An interview guide is prepared in order to ensure that basically the same information is obtained from a number of people by covering similar material. The interview guide provides topics, or subject areas, within which the interviewer is free to explore and ask questions that will illuminate the particular topic. The conversational style is maintained because the interviewer is free to build a conversation within a particular subject area, and to spontaneously pose questions, but with a focus on a

particular topic that has been predetermined. Use of an interview guide makes sure that the researcher has carefully decided how best to use the limited time available in an interview situation (Patton, 1990:283).

Although the informal conversational interview, complemented by the interview guide, will dominate the interview methodology of this research, some specific questions, discovered through the literature review and case study, demand responses from each category of respondent, and shall be directly pursued. Appendix A presents the interview guide, outlining the topics specific to each respondent category, as well as providing a list of the specific questions to be pursued.

Although the interview guide will help to ensure that similar information is gathered, often times the data gathered from informal conversational interviews will be different for each person interviewed depending on the perspective of the respondent. In many cases, the same person may be interviewed on a number of different occasions using an informal, conversational approach. Interview questions and topics may even change over time, as each new interview builds on the preceding ones, expanding information that was previously learned, moving in new directions, and seeking responses by categorical respondents based on responses to similar topics by respondents of other categories (Patton, 1990:282).

The strength of the informal conversational approach is that it allows the researcher to be highly responsive to individual differences and situational changes, embarking on any

conversational direction the interviewer or respondent deems appropriate. Furthermore, questions can be individualized, drawing on the particular topics that the respondent is most intimate with rather than wasting both the researcher and the respondent's time on issues not central to the respondent's knowledge base.

Although the individualization of questions is a strength of the informal conversational interview, it is a weakness as well. Because a systematic set of questions is not administered throughout each interview, it takes a greater amount of time to collect relevant information. This is a result of the high probability that it may take several conversations with different people before a similar set of questions has been posed to each participant in the interview process. Also a weakness of the informal interview is the fact that it relies on the conversational skills of the interviewer to a greater extent than do formal, standardized formats (Patton, 1990:282). The conversational interviewer must be able to interact easily with the respondents in a variety of settings, generate rapid insights, formulate questions quickly and smoothly, and guard against asking questions that are misleading, or formed with built-in bias.

Data from informal conversational interviews are difficult to arrange in a manner that is easily analyzed. Because different questions will generate different responses, the researcher has to spend a great deal of time reviewing responses to find trends that have emerged at different points in different interviews with different people. Conversely, interviews that are more systematized and standardized facilitate analysis but provide less

flexibility and are less sensitive to individual and situational differences (Patton, 1990:282).

Elite Interviewing

While the interview methodology of this research is primarily informal conversation oriented, what Marshall and Rossman (1989:94) term *elite interviewing* will be a concurrent interviewing methodology. Elite interviewing focuses on a particular type of respondent. Elites are those individuals considered to be "...influential, prominent, and well-informed people in an organization or community" (Marshall *et al.*, 1989:94). Elites are selected for the interview process on the basis of their expertise and intimacy with the areas relevant to the research. Rather than interviewing a cross-section of the American public, the four categories of respondents selected for this study, technology developers, technology users, consultants, and environmental regulators, were selected completely on the basis of their position relative to the transfer of an environmental remediation technology, thereby deeming the interview strategy one of not only informal conversation, but also one of elitism.

Advantages of elite interviewing are rooted in the fact that the respondents are directly involved in the phenomena being researched. Elites can usually provide an overall view of the focus system, or process and provide insight to its relationship to other systems and processes. Likewise, they are more likely than other possible respondents to be familiar with the legal and financial structure of a system or process. Elites also offer depth of knowledge about policies, past histories, and future plans relevant to the research topic (Marshall *et al.*,1989:94).

The major disadvantage of elite interviewing is that elites are often difficult to access. This is because elites are usually busy people, deeply involved in their particular field of employment, operating under demanding time constraints. Many times the interviewer must rely on "...sponsorship, recommendations, and introductions..." for assistance in making elite contacts (Marshall *et al.*, 1989:94). The elites to be interviewed include technology developers, technology users, consultants, and environmental regulators.

Technology Developers

Technology developers are those people directly involved in the process of creating an environmental remediation technology. They may be those who had the initial conception of the process or those tasked with the exploration and experimentation of the idea to move it from merely a conception to reality. Technology developers, as they relate to this thesis, can be found in government laboratories, private laboratories, academia, or private firms –virtually anywhere. The technology developers most central to this thesis are those who have operating expenses funded through government resources. Therefore, government-funded laboratory scientists and academics make up many of the environmental remediation technology developers who will be interviewed as part of this study.

Technology Users

Technology users are individuals or organizations tasked with remediating contaminated sites. They are the people who select and employ an environmental remediation

technology at a particular site. In the Air Force, these individuals, commonly called remedial project managers, are primarily located at the base level and work in the environmental management flight. However, remedial project managers may work at a major command, overseeing numerous bases and individual hazardous waste sites.

Consultants

Consultants are individuals specializing in site characterization and technology recommendation. Most commonly, consultants work for a private firm that is hired by a site owner needing the environmental expertise of the consultant to determine the proper course of action to remediate a site. Although most consulting agencies are private firms, not all are. For example, AFCEE, mentioned in Chapter 2, provides some of the consulting services for the remediation of Air Force sites.

Environmental Regulators

Tasked with overseeing environmental cleanup operations, environmental regulators ensure that restoration activities comply with federal, state, and local environmental laws. These individuals must be convinced of an innovative technologies ability to perform as it is intended at a particular site for the ultimate employment of the technology to become reality. The primary evaluation criteria, the CERCLA performance criteria, used by environmental regulators was presented in Chapter 2. EPA regional offices are the natural starting point for access to and interview of environmental regulators. Likewise, state and county regulatory agencies are sources of information from a regulator's perspective.

Indicated earlier, in qualitative research methods, the sample size of each elite group to be interviewed is not predetermined (Patton 1990:14). A brief discussion outlining sample size strategy of this thesis is presented.

Qualitative Study Sample Size

Typically, qualitative research produces a wealth of detailed information about a small number of people or situations, increasing the understanding of the cases and interactions relevant to the topic under evaluation, but reducing generalizability (Patton 1990:14). When embarking on interview research, the interviewer naturally desires to interview a large number of respondents. However, the definition of "large" in qualitative research is relative to the topic being researched and not quantitatively defined. Patton (1990:14) suggests that with the same fixed resources and time, a researcher may opt to study a large number of people, seeking breadth, or a small number of people, seeking depth. While the NRC (1997) has conducted extensive research aimed at identifying the regulatory and systematic barriers that hinder the transfer of an environmental remediation technology, there is little research focusing on the methods to overcome these barriers at the level of the individual technology developer. And even though general technology transfer has been researched extensively, with the *Journal of Technology Transfer* being devoted to reporting technology transfer findings, there have been few articles published in the journal focusing on environmental remediation technology. So, while the basis of technology transfer is somewhat well defined, giving breadth to the knowledge base, little in-depth knowledge on the transfer of an

environmental remediation technology from the developer's perspective has been documented. Furthermore, it is unclear whether the general rules of technology transfer apply to the field of environmental remediation technology. Our goal in this endeavor therefore shall be to seek out as many respondents as possible, being careful to validate current rules of technology transfer while seeking in-depth knowledge of the specific rules, not necessarily applicable to other technology fields, that govern the transfer of an environmental remediation technology.

Telephone Interviews

Although some of the informal conversational interviews will be conducted in person, many of them will be conducted over the telephone. The telephone interview is an alternative to face-to-face interviews that has had a justifiably poor reputation for some time (Dane, 1990:131). At one time, the problem with telephone interviews was that few people actually owned phones from which the interview could be conducted. This era has long since passed, but unfounded lingering skepticism about telephone interviews is still apparent. In 1978, Klecka and Tuchfarber used a telephone interview strategy to replicate a study that had been done via face-to-face interviews. They found no appreciable differences between the results of their telephone interviews and those of the original face-to-face interviews. Thus, the lingering skepticism of telephone interviews is no longer justifiable (Dane 1990:131). Furthermore, the use of telephones permits collaboration with elites across the country, or on the other side of the world, if deemed necessary.

Conclusion

Convergent methodology is not suitable for all research purposes. It is difficult, if not impossible, to replicate and various constraints, such as time, may prevent its use (Jick, 1983:146). Nevertheless, convergent methodology has vital strengths and encourages productive research. As demonstrated in this chapter, use of convergent methodology for this research is appropriate. While no single methodology is free of problems, convergent methodology strives to reduce the error inherent in each methodology pursued by requiring trend verification by an alternative method.

The three sources of data, literature review, case study, and interviews, provide a rich research foundation from which trends will be sought. Furthermore, the three catagories of elites identified for interviewing, technology developers, technology users, and environmental regulators, were selected based on their position relevant to environmental remediation technology transfer and should provide a solid knowledge base about the process.

Many authors contend that, in qualitative research, the use of more than one research method can provide credibility to the work and therefore, use of multiple methods has become a quite useful tool (Jick,1983:135; Marshall *et al.*, 1989:146; Patton, 1990:187). In pursuit of the factors that govern the transfer of an environmental remediation technology, this research shall adhere to the convergent methodology principles described in this chapter.

One researcher, when writing on qualitative research development, put it this way:

> *No single method ever adequately solves the problem of rival casual factors...Because each method reveals different aspects of empirical reality, multiple methods of observation must be employed...I now offer as a final methodological rule the principle that multiple methods should be used in every investigation.* (Denzin, 1978:28)

IV. Case Study: In-Well Air Stripping (NoVOCs)

Introduction

This chapter reviews one technology, in-well air stripping, that has progressed from concept to commercialization (Figure 2-1). A review of in-well air stripping, also known by the trade name NoVOCs, is presented to illustrate the transfer of an environmental remediation technology from full-scale demonstration to implementation. Through careful review of the events that moved NoVOCs to commercial implementation, we hope to reveal those actions or processes most critical to it's successful transfer.

Overview

An overview of NoVOCs technology is presented to provide the reader with a general understanding of the technology. Individual environmental remediation technologies are based on particular processes, and these processes may pose particular barriers that must be overcome for the transfer of the technology to become reality. Therefore, a case study of the transfer of one environmental remediation technology will not necessarily present all of the barriers that may arise when transferring other technologies. A general understanding of NoVOCs technology will provide the reader with an appreciation of the specific barriers that may arise when commercializing similar technologies. In addition, the case study will reveal other, more general issues, which influence technology commercialization, such as the use of patents or the use of full-scale technology demonstrations.

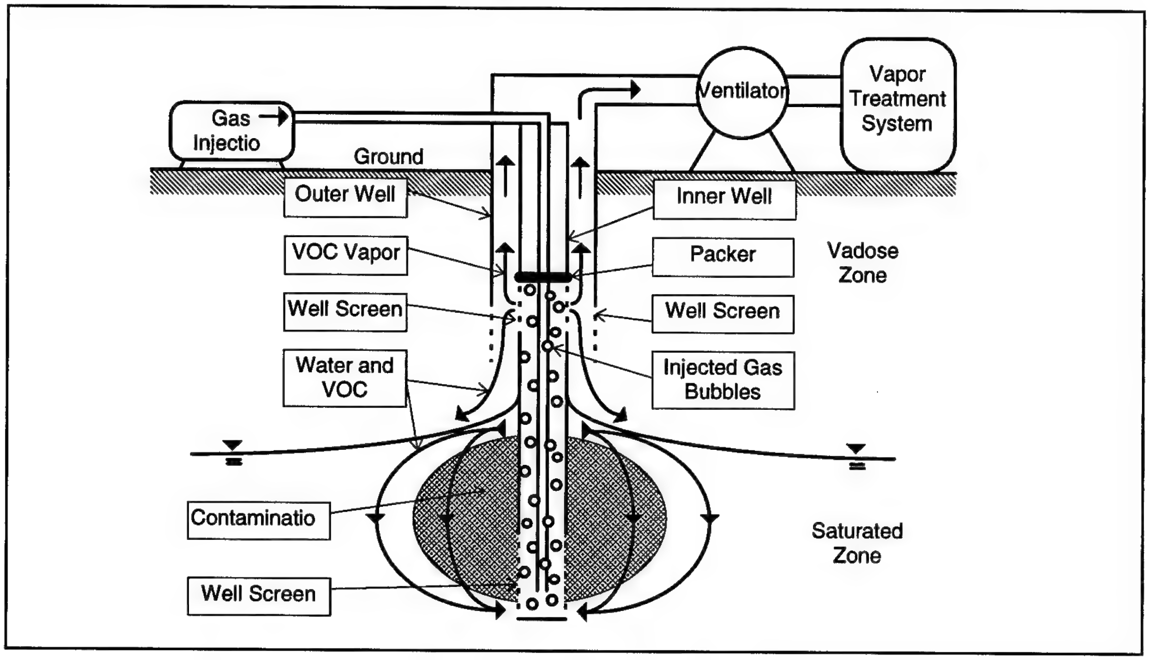
NoVOCs Technology Description

NoVOCs is a technology that creates an air-stripper inside of a treatment well. The air-stripper volitalizes the Volatile Organic Compounds (VOCs) contained in the groundwater and removes the contaminants as vapor for treatment. Figure 4-1 provides a graphical representation of NoVOCs technology.

NoVOCs uses a well design that houses one well within another. The inner well extends from the ground surface through the vadose zone and into the saturated zone where it is screened in the contaminated zone. The outer well extends from the ground surface through the vadose zone where it is most commonly terminated just above the water table. However, the outer well may extend into the saturated zone where it is screened in the zone of contamination. A gas injection line is inserted in the inner well and releases air below the zone of contamination. This creates rising gas bubbles that collect VOCs which are transferred from the liquid phase to the gas bubbles. Due to airlift pumping, the bubbles and water rise in the inner well until they encounter a deflection plate, commonly called a packer, above the water table. The packer separates the bubbles from the water. In the area of the packer, the inner well is screened, allowing the water and air bubble mixture to enter the outer well. The water falls through the outer well and returns to the saturated zone. The vapor from the gas bubbles is vacuumed off by a vacuum line extending into the outer well. The VOC-rich vapor is the then treated aboveground using such methods as carbon adsorption, biofiltration, or catalytic oxidation. By returning the partially cleaned water to the saturated zone, a recirculation system is established allowing multiple passes of the water through the in-well system. This circulation

sequentially removes the VOCs from the groundwater causing the groundwater to become less contaminated with each pass (Gvirtzman and Gorelick, 1993; In-Well, 1997:28; Stanford University, 1997).

Figure 4-1. In-Well Air Stripping (After Stanford University, 1997)



Technology Progression

This section is based on interviews of key members in the development and transfer of NoVOCs technology. It synthesizes the interview data gathered from the primary developer of the technology (Gorelick, 1997), and key employees at two firms, EG&G Environmental (Dawson, 1997), and Metcalf and Eddy (Shattuck, 1997) that licensed the technology.

In the late 1980s, NoVOCs was developed by Stanford University researchers who filed for a United States patent for the technology in May, 1991. A patent, number 5180503, was subsequently awarded in January 1993 (Gorelick and Gvirtzman, 1993). A second patent, number 5389267, that slightly modified the original patent and covered the combination of NoVOCs with *in situ* bioremediation and soil vapor extraction was awarded in February 1995 (Gorelick and Gvirtzman, 1995). Because the technology was developed by Stanford University researchers, the university owned the patents.

In order to facilitate the transfer of the technology, the primary researcher on the Stanford team established NoVOCs Incorporated in 1993 which is the origin of the trade name, NoVOCs, for in-well air stripping. The company soon obtained rights to the technology from Stanford University.

ICF Kaiser Engineers, a large environmental firm, had interest in the technology in the early stages of development —even prior to the first peer-reviewed publication describing the technology, published in 1992 (Gvirtzman and Gorelick, 1992). ICF Kaiser Engineers gained interest in the technology through one of its employees who chaired an innovative technology panel under DoE's VOC -Arid Site Integrated Demonstration Program. Because the employee was well informed about innovative environmental remediation technologies, he saw the potential of this technology to be successful early in its development. ICF Kaiser Engineers tasked the employee with negotiating an agreement with NoVOCs Inc. for the rights to implement the technology in France. The original demonstration site suggested by ICF Kaiser Engineers was rejected by NoVOCs

Inc. due to technical reasons. However, an alternative site, in Aubagne, France was accepted and ICF Kaiser Engineers was granted the rights to implement the technology in France.

The demonstration in Aubagne, France was on a PCE contaminated plume at a pigment manufacturing site. The demonstration was considered a success as concentrations were reduced as much as 98% with average reduction being 91% (Metcalf & Eddy, 1997:29). After the successful demonstration, ICF Kaiser decided to pursue world wide rights to the technology. The same employee that had negotiated with NoVOCs Inc. for the rights to implement the technology in France was called upon again to negotiate for world wide rights. After reaching an agreement with NoVOCs Inc. for world wide rights, ICF Kaiser Engineers decided not to follow through with the proposition due to a corporate decision to avoid "technology vending." As consultants, ICF Kaiser Engineers felt that to give their clients the best objective services, the firm needed to remain free of proprietary interests in any particular technology. Additionally, the firm felt they lacked the necessary staff and infrastructure to sell the technology.

Soon after ICF Kaiser Engineers decided to forgo the opportunity to obtain world wide rights to the technology, EG&G, a large technology and systems integration company, approached the ICF Kaiser Engineers employee who had negotiated the prior deals with NoVOCs Inc. and offered him a position with EG&G. The position entailed the establishment of an environmental division at EG&G which the employee would head. The employee accepted, and nine months later, in September 1994, EG&G

Environmental acquired NoVOCs Inc., thereby gaining ownership of commercial rights to the technology.

With much involvement of the primary researcher at Stanford University, the new president of EG&G Environmental scheduled, through the panel he chaired under the VOC -Arid Site Integrated Demonstration Program, a demonstration of the technology at the DoE Hanford site in Washington. The demonstration was to take place in January 1995. EG&G's strategy was to blitz the environmental technology market based on data collected in Aubagne and at the Hanford site. Plans were in place to produce a design manual and nomographs capable of providing a site owner with a quick method of determining if the technology may be appropriate for their particular site. Meanwhile, in addition to publishing a second peer reviewed paper (Gvirtzman and Gorelick, 1993), the primary researcher at Stanford University was actively seeking additional outlets to gain recognition of the technology among the environmental community. One outlet that was utilized that, according to the researcher, gave "credibility" to the technology was the publication of a short article about the technology in *Business Week* (Breath of Fresh Air, 1992:62).

To the disappointment of the newly established EG&G Environmental division, the Hanford demonstration was postponed until January 1996 and moved to Edwards Air Force Base in California. The Hanford demonstration was plagued with difficulties stemming from an attempt to demonstrate multiple technologies concurrently. Faced with the reality that additional data to complement the data from the Aubagne

demonstration would not be gathered for quite some time, EG&G Environmental built bench-scale models in acrylic aquariums (12" x 18" x 2.5" and 24" x 36" x 4") to demonstrate the technology to potential buyers. Additionally, a full size unit was tested and demonstrated in a swimming pool. Upon seeing the aquarium and swimming pool demonstrations, potential buyers were intrigued by the technology but wanted hard data from a real demonstration site. The data from Aubagne did not satisfy this need, according to the president of EG&G Environmental, simply because United States buyers would not accept data from a demonstration conducted on foreign soil. Additionally, the cleanup standard for PCE, the contaminant at Aubagne, in France is 1 ppm, while the United States cleanup standard is 5 ppb. Although the French cleanup standard was attained, the demonstration was not continued to reach the United States cleanup standard.

In January 1996 the technology demonstration at Edwards AFB began on a TCE contaminated plume. The demonstration had a minor glitch that was not foreseen during site characterization –the aquifer at Edwards AFB is semi-confined. This limited the ability of the system to establish and demonstrate groundwater recirculation. However, by increasing the volume of injected gas, treatment goals were attained.

With successful demonstrations at both Aubagne and Edwards AFB, technology users were convinced that the technology worked, at least for specific geologies. While the interest of technology users in the technology was peaking, EG&G Environmental began offering performance guarantees. The guarantees are based on one pilot well that can be

used as part of a full-up system if the pilot test is successful. The performance guarantee clearly defines the percent of contaminant that will be removed and the radius of influence the treatment well will achieve. Additionally, a performance period is sometimes guaranteed, but only if site characterization (supplied by the site owner) is not flawed –it is unreasonable to bind a technology vendor to a performance agreement when site characterization information, specifically subsurface geology characteristics, that have been gathered and supplied by the site owner are inaccurate.

As EG&G Environmental continued to actively market NoVOCs technology, the firm realized that the size of the firm, varying from 10 to 18 employees, was not large enough to have the market presence required to effectively market the technology. In the fall of 1996, EG&G Environmental decided to license Metcalf & Eddy, a large air and water technologies company, to implement the technology in 20 states. Metcalf & Eddy had the market presence and staff necessary to effectively market the technology.

The senior staff at Metcalf & Eddy has a vision of Metcalf & Eddy becoming a leading vendor of innovative environmental remediation technologies, making NoVOCs a perfect candidate technology for the company. Before pursuing the NoVOCs license, Metcalf & Eddy consulted with regulatory agencies to determine how the technology would fare in a review against the CERCLA criteria. A strong presence in each of the 10 EPA regions, as well as a good working relationship with the EPA regulators, led to candid responses from regulators evaluating the technology. Because the regulators favorably reviewed the technology and the fact that Metcalf & Eddy is establishing itself as a vendor of

innovative technologies, the incentive existed for Metcalf & Eddy to pursue a NoVOCs license.

Metcalf & Eddy had an additional incentive to obtain a license to the technology. In 1995, an employee of Metcalf & Eddy began attending site meetings at the Massachusetts Military Reservation (MMR) site, Cape Cod, Massachusetts. At these meetings, it was learned that a similar in-well technology of German origin called UVB (Unterdruck-Verdampfer Brunner) was not performing well. A number of factors made the site a high visibility site. For example, the area is a frequent vacation spot for the President and Vice President of the United States and many prominent political figures have residences in the vicinity of Cape Cod. Metcalf & Eddy realized that poor remediation efforts at the site would not be tolerated for any appreciable amount of time and believed that NoVOCs technology would be appropriate for the site.

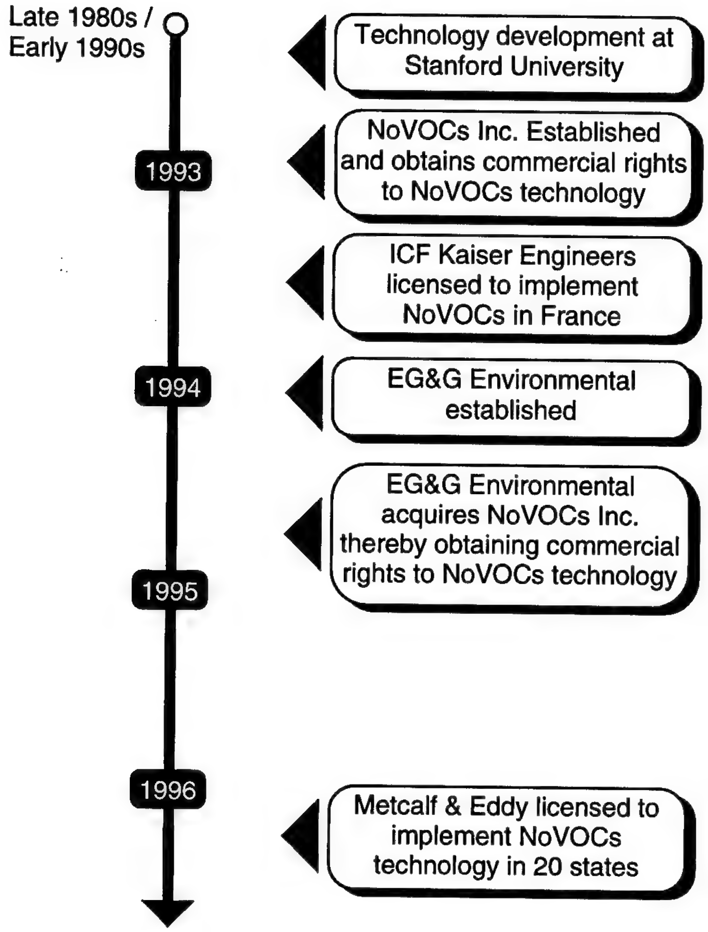
The MMR site remediation program, originally the responsibility of the National Guard, was moved to AFCEE. Likewise, the primary site contractor, Optec, was removed and the contract was awarded to Jacobs Engineering Group. With a fresh staff responsible for the remediation of the MMR site, Metcalf & Eddy, now with a license to implement NoVOCs technology, was soon subcontracted by Jacobs Engineering Group to perform a six month pilot test/demonstration of the technology at the site.

Although there were some initial problems with the pilot test that, according to Metcalf & Eddy, were caused by "poor site characterization" provided by the original primary

contractor, Optec, the demonstration was a success. The six month demonstration removed more than 450 lbs. of TCE — more than any other technology being employed at the site. Even though the technology was to be discontinued after the six month pilot test until full-scale remediation efforts begin in 1999, local community residents argued to keep the NoVOCs system operational. The residents were successful and the NoVOCs system continues to operate at the MMR site (at the time this thesis was written).

Since granting the technology license to Metcalf & Eddy, EG&G Environmental and Metcalf & Eddy have implemented the technology at a number of locations. In fact, company brochures for the two firms detail 15 different sites and provide case studies of each of them (EG&G Environmental, 1997; Metcalf & Eddy, 1997). Additionally, the technology has been scheduled for an EPA SITE program (described in Chapter 2) demonstration project to be conducted at the North Island Naval Air Station site.

Figure 4-2. Commercial Interest/Involvement with NoVOCs Technology



The above discussion illustrates the progression of NoVOCs from its original development at Stanford University to its current status as a technology that has been successfully transferred and is in commercial use. Figure 4-2 traces the commercial interest in the technology. The following section details the mechanisms of technology transfer (described in Chapter 2) that were utilized in the transfer of the technology.

Technology Transfer Methods Utilized in the Transfer of NoVOCs

Many of the technology transfer mechanisms described in Chapter 2 were employed in the successful transfer of NoVOCs. This section discusses each of the mechanisms used. For convenience of recollection, Table 2-5 is reproduced below as Table 4-1 and outlines many of technology transfer methods discussed in Chapter 2.

Table 4-1. Technology Transfer Mechanisms

GENERAL	EXAMPLES
Advisory Groups	*End User Review Groups* *Technical Review Groups*
Collaboration With Cost-Sharing	*Industry Consortia* *Cooperative R&D* *Demonstration Projects* *User Facilities*
Collaboration Without Cost-Sharing	*Contracting R&D*
Personnel Exchanges	*Work for Others* *Staff Consulting* *Guest Staff* *Staff Transfers*
Licensing/Spinoffs	*Licensing* *Spinoff Companies*
Active Dissemination of Information	*Broker Organizations* *Workshops, Seminars, or Conferences* *Information Centers* *Education*
Passive Dissemination of Information	*Mailings* *Technical Reports* *News Releases* *Journal and Magazine Articles* *Fact Sheets* *Videotapes* *Decision Tools* *Electronic Bulletin Boards*

Cooperative Research

The demonstration conducted in Aubagne, France was clearly instrumental in the development of NoVOCs technology. Although a formal research agreement was not

established, the role played by ICF Kaiser Engineers in the development of the technology is evident –Aubagne represented, in fact, the first set of data collected from an actual contaminated site. The involvement of ICF Kaiser could be called what Winebrake terms "Collaboration with Cost Sharing", reviewed in Chapter 2 (Winebrake, 1992:57). While most of the initial development of the technology was funded through research grants obtained by Stanford University researchers, the demonstration at Aubagne was completely funded by ICF Kaiser Engineers. The involvement of a commercial partner in the development of the technology was instrumental. Although the development of the technology was initially modified technology push, the involvement of a commercial firm soon after the early developmental stages of the technology led to a transfer process that could be considered market pull.

Licensing/Spinoffs

Both licensing and spinoff strategies were employed in the transfer of NoVOCs technology. Spinoff companies are companies that are created exclusively to enhance the transfer of a technology or to obtain the commercial rights to a particular technology. The establishment of NoVOCs Inc. by the primary researcher at Stanford University clearly fits the definition of a spinoff company. By establishing this company, commercial rights to the technology could be obtained and a license could be granted to ICF Kaiser who was planning a demonstration of the technology. In addition to licensing ICF Kaiser, the technology was also licensed to Metcalf & Eddy. Even EG&G Environmental could be considered a spinoff company. Although EG&G Environmental

does offer other environmental technologies, its initial establishment was clearly centered on the market potential of NoVOCs technology.

Patenting the technology played an important role in the transfer of NoVOCs. ICF Kaiser Engineers, EG&G Environmental, and Metcalf & Eddy all recognized the potential of the technology and therefore had incentive to obtain commercial rights to the technology. It is important to note that NoVOCs was patented well before any government funding was received for the development of the technology, thereby ensuring that Stanford University would own the patent. Had government funding been involved prior to the granting of a patent, the government would own the patent and the technology would be public domain. It is difficult to speculate whether interest in the private sector would have been as substantial had there not been a possibility of obtaining a technology license, but clearly the financial incentive to obtain a license to implement NoVOCs was important to the private firms involved.

Dissemination of Information

Many methods were used to disseminate information. Each of them is discussed below.

Conferences / Seminars: The primary researcher and developer of the technology routinely addressed the scientific community at conferences and seminars throughout the development of the technology. His remarks centered on the experimental results of the technology and applications for its use. Likewise, as a leading air and water technology company, Metcalf & Eddy attends and sponsors conferences and seminars at which they

present NoVOCs discussions regularly. Although the technology has been transferred to a commercial firm, it is important that the commercial firm implementing the technology continue to actively disseminate information in order to capture more of the environmental remediation technology market.

Bench Scale Demonstrations: In addition to bench scale demonstrations conducted at Stanford University, EG&G Environmental conducted bench scale demonstrations in acrylic aquariums. The demonstrations were not conducted in a laboratory where interested parties would have to be present to view, but rather, EG&G Environmental would meet with PRPs, consultants, and regulators and perform the demonstrations in their presence so they could witness the technology working in real time. According to EG&G Environmental, the demonstrations were instrumental in gaining the interest of potential technology users. Providing the potential user with something they could see and touch, rather than a technical report that was difficult to understand, often gave the potential user something that, according to EG&G Environmental, is important to the implementation of a technology –understanding of the technology on the part of the technology user.

Mailings: Both EG&G Environmental and Metcalf & Eddy use this method of information dissemination. Information provided in the mailings include an explanation of the technology along with technology illustrations, parameter ranges of parameters crucial to technology performance, multiple case studies describing the performance of the technology at sites where NoVOCs has been used, and cost effectiveness data. An

important aspect of the mailings, according to Metcalf & Eddy, is that the mailings are not simply mass mailings to unknown receptors, but that each person receiving a mailing is identified by name in the mailing. This extra effort may be enough to keep the mailing from being discarded as "junk mail."

Technical Reports: Technical reports on NoVOCs technology have been compiled. For example, a detailed technical report outlining the efficacy of NoVOCs has been completed based on the performance of the technology at the MMR site (Parsons Engineering Science, 1997). Technical reports may be completed based on laboratory study, but are more useful if compiled after a field-scale demonstration. Field-scale evaluation provides the necessary data needed to compile a technical report describing the technology and detailing its performance at an actual site.

News Releases: News releases offer a quick way of distributing information about the availability of an innovative technology. While they can not replace journal publications because there is no peer-review or scientific scrutiny, they do offer an expedient method of distributing less technical information about the technology. Stanford University, EG&G Environmental, and Metcalf & Eddy all used news releases as a method of marketing the technology.

Magazine Articles: Like news releases, magazine articles offer a somewhat quicker way of disseminating information than do journal articles. Though again, they do not offer the degree of scientific scrutiny offered by journal publications. They do, however,

seem to be somewhat more credible than news releases. Many magazine articles have been published about NoVOCs technology (Cichon *et al.*, 1996:40; Industrial Wastewater, 1997:28; Initiatives, 1997; Owendoff, 1996:2). Most of the magazine articles reviewed gave explicit directions on how to obtain more information about the technology and in many instances gave the name of a contact person. After providing a brief overview of the process by which NoVOCs cleans up a VOC contaminated site, the articles primarily focused on the ease of use, low cost, and reduced cleanup time offered by the technology.

Journal Articles: Although a more lengthy process is required to publish in a journal, journals offer the scientific scrutiny required by many technology users and regulators. Journal articles have been published (Gvirtzman and Gorelick, 1992; Gvirtzman and Gorelick, 1993) focusing on the technical data describing NoVOCs that the news releases and magazine articles lack. In the case of NoVOCs, the news releases and magazine articles were clearly a valuable tool used to capture the interest of potential users but without peer-reviewed literature few regulators would have given the technology serious consideration. In addition, the peer-reviewed journal articles were crucial to the decision of Metcalf & Eddy to pursue a technology license.

Videotapes: A video describing NoVOCs and its advantages over pump-and-treat technology has been made available through the DoE Office of Environmental Management (DoE, 1995). Videotapes offer a visual picture of the technology and can be effective in gaining the interest of potential users. The videotape lends further credibility

to the technology and is also an innovative marketing tool not always employed by technology vendors. An "extra" step taken to commercialize a technology, such as the distribution of a videotape, may be what sets a particular technology apart from the field of others.

World Wide Web/Internet: Descriptions and illustrations of NoVOCs technology are quite accessible on the internet. Stanford University and Metcalf & Eddy both make use of the internet to market NoVOCs and passively disseminate information about it (Stanford University, 1997; Metcalf & Eddy, 1997). Both sites offer process descriptions, illustrations, and contacts to obtain more information on the technology. It is unclear how productive this method of disseminating information has been. What is clear is that other organizations have helped to lend credibility to the technology by including explanations of the technology on their internet sites. For example, without prompting by the primary researcher at Stanford University or either of the commercial vendors of the technology, DoE's Office of Environmental Management has included a description of the technology at the office's internet site (DoE Office of Environmental Management, 1997). Clearly, the mere inclusion of the technology on an internet site owned by DoE, an organization that is responsible for cleaning up the most contaminated sites nationwide, helps promote the technology by giving it credibility among the environmental community.

Laboratory / Site Visits

According to Metcalf & Eddy, site visits by regulators, technology users, and consultants, are one of the most important aspects of technology marketing and transfer. Metcalf & Eddy claims to extend weekly invitations to these groups to visit sites were NoVOCs is in operation. According to Metcalf & Eddy, a site such as the MMR site is ideal for site visits. Not only is it a vacation area, providing incentive to visit the site, but it also offers an opportunity to view NoVOCs technology side by side with a competing technology, UVB.

Field-Scale Technology Demonstration

NoVOCs was evaluated at field-scale two times before any regulators or site owners selected the technology for use at their site. The first demonstration, in Aubagne, France was successful but proved to be of little use when trying to implement the technology in the United States. The two reasons for this are that first, the demonstration was performed outside of the United States leading to skepticism about the ability of the technology to perform in the United States as well as it had reportedly performed in France, and second, the allowable contaminant level in France, and therefore the treatment goal, is considerably less stringent than that required in the United States. Even though the demonstration provided hard data, the fact that it was carried out in an unfamiliar location on foreign soil rendered the data less acceptable to regulators, technology users, and consultants in the United States.

The second full-scale demonstration of NoVOCs was conducted at Edwards AFB. In many ways, this demonstration provided what the demonstration in Aubange lacked – cleanup overseen by United States environmental regulators at a familiar location in the United States. Lessons learned from this technology demonstration can be applied to the transfer of any environmental technology. For example, although the demonstration was vital to the transfer of NoVOCs, the demonstration was delayed an entire year and moved from its originally scheduled location at the Hanford site in Washington to Edwards AFB in California. This delay caused the sole commercial vendor of the technology at the time, EG&G Environmental, to be forced to find innovative marketing tools, such as aquarium demonstrations, to increase interest in the technology. Additionally, the delay substantially impacted projected earnings of EG&G Environmental. Another problem with the demonstration was that the government-purchased equipment used for the demonstration was oversized and more powerful than required. This led to blown seals, and inefficient operation. Much of the equipment finally used in the demonstration was purchased by EG&G Environmental at a much lower cost. Although the non-government entities involved with the demonstration concede to the fact that the demonstration probably never would have been possible without government involvement (funding and test site), they unanimously assert that government inefficiencies in coordination of activities and system mobilization probably set the full-scale commercial implementation of the technology back nearly two full years. While technology demonstrations were obviously critical to the transfer of NoVOCs, the degree of planning that is put in to them may have massive financial and temporal implications.

The preceding description of the multiple methods of technology transfer provides a clear illustration of the fact that a single method of technology transfer is rarely, if ever, capable of leading to the full-scale commercial implementation of an environmental remediation technology. It is also important to recognize that in the case of NoVOCs, strong interest and backing by a commercial entity played a large role in the acceptance of the technology by regulators and technology users. Many of the mechanisms of technology transfer were actually initiated by the commercial vendors of the technology rather than the technology developer. Figure 4-3 re-illustrates Figure 4-2 with the inclusion of technology transfer methods utilized in the transfer of NoVOCs.

CERCLA Performance Criteria and NoVOCs

Chapter 2 presented an overview of the nine CERCLA performance criteria used to evaluate environmental remediation for deploying a technology at a particular site. The nine criteria are displayed in Table 4-2.

Figure 4-3. NoVOCs Technology Transfer Methods Timeline

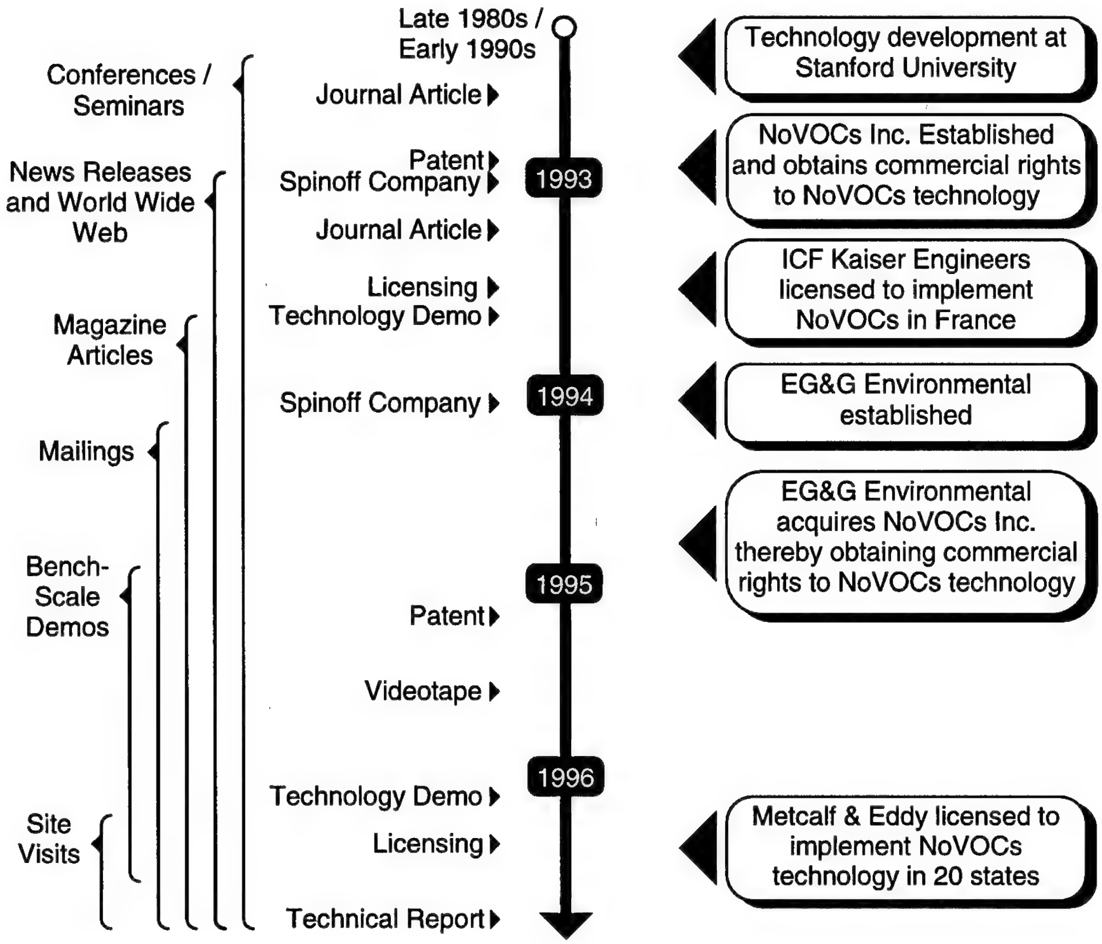


Table 4-2. CERCLA Technology Performance Criteria

1. Overall protection of human health and the environment
2. Compliance with all other applicable or relevant and appropriate requirements (ARARs)
3. Long-term effectiveness and permanence
4. Reduction of toxicity, mobility, or volume through treatment
5. Short-term effectiveness
6. Implementability
7. Cost
8. State acceptance
9. Community acceptance

As discussed in Chapter 2, for an innovative technology to have any real chance of being transferred and commercially implemented at those sites where it is applicable, it must satisfy the CERCLA performance criteria at least as well as the traditionally accepted remedies. The CERCLA performance criteria shall be revisited here with a brief discussion of how well NoVOCs satisfies each of the criteria.

Overall Protection of Human Health and the Environment

This criterion is one of the two threshold criteria, meaning that NoVOCs must fully satisfy this criterion to be considered for implementation at a contaminated site. As an assessment to determine whether the technology will function in a safe manner that will provide adequate protection to human health and the environment, this criterion is closely related to other criteria, especially long-term effectiveness and permanence, short-term effectiveness, and compliance with ARARs. Because NoVOCs satisfies each of the other criteria at least as well as traditionally accepted technologies (discussed below), it satisfies this encompassing criterion of overall protection of human health and the environment.

Compliance with ARARs

This threshold criterion is used to determine how well a proposed environmental remediation technology complies with federal, state, and local environmental laws. At the more than fifteen sites that NoVOCs has been implemented at or considered for implementation, the designs have assured this criterion is met.

The next five CERCLA performance criteria are balancing criteria. The performance of NoVOCs does not have to fully satisfy each of these criteria. Instead, the criteria are used as overall performance indicators, meaning that for NoVOCs to be selected for implementation at a site, it must demonstrate the best overall performance relative to these criteria when compared to alternative environmental remediation technologies.

Long-Term Effectiveness and Permanence

This criterion will be used to evaluate the ability of NoVOCs to reliably protect human health and the environment, after the cleanup is completed. Under this criterion, EPA has generally favored permanent treatment technologies (destruction) over technologies that pose the possibility of contaminants being re-released to the environment (containment). EPA also favors technologies that treat contaminants at the site rather that those that require removal to off-site locations (Skumanich, 1994:418). NoVOCs permanently removes the contaminant from the groundwater and, at a minimum, the contaminant is concentrated through an off-gas treatment system and removed from the site. Because the contaminant is removed from the groundwater –permanently, NoVOCs is evaluated favorably under this criterion.

Reduction of Toxicity, Mobility, and Volume through Treatment

The objective of this criterion is to measure the degree to which NoVOCs includes destruction of the contamination, as opposed to containment or disposal elsewhere. Since NoVOCs fails to fully degrade the contaminants into innocuous substances *in situ*, forcing them to be transferred to an off-gas treatment system, there has been some

concern over the use of NoVOCs relative to this criterion. However, many other technologies that are commonly acceptable, such as pumping and treating with traditional air stripping, use a similar process of stripping contaminants and concentrating them in the solid phase. NoVOCs does treat the contaminant at the site rather than transporting it before treatment. The on-site treatment leads to a reduction in contaminant mobility and volume. Overall, NoVOCs is met with little resistance stemming from this criterion.

Short-Term Effectiveness

Under this criterion, technologies favored are those that require a relatively short and uncomplicated construction period and a relatively short time to implement. Additionally, those technologies that pose the least disruption to the environment are preferred as are those whose impacts to the environment can be easily monitored. NoVOCs poses little disruption to the environment, certainly no more than other vapor stripping. The only short-term risks faced by workers are associated with the off-gas treatment. Anytime contaminants are brought to the surface for treatment, worker risk is involved. Although the short-term risk to workers is minimal and NoVOCs is not reviewed poorly under this criterion, it is not reviewed as favorably as *in situ* treatment technologies which pose almost no short-term risk to workers.

Implementability

The objective of this criterion is to measure the technical and administrative feasibility of a proposed remedy. Implementation of NoVOCs is quite easy, requiring little in the way of material or labor. In terms of general availability of goods and materials, the

technology receives favorable evaluations under this criterion. A critical aspect of this criterion is how well the technology has been demonstrated for use, and how reliable the technology will be once it is fully operational. With nearly 15 case studies documenting the performance of the technology, regulator acceptance barriers are virtually non-existent. Even during the first few full-scale implementations of this technology, little regulatory resistance was encountered. In all, the technology has already been approved by regulators in twelve states including Arizona, California, Florida, Idaho, Indiana, Kansas, Massachusetts, New Hampshire, New York, Virginia, Washington, and Wisconsin.

Cost

The objective of this criterion is to identify technologies that have reasonable costs, not necessarily the technology with the lowest cost. NoVOCs is highly acceptable with regard to this criterion. Capital cost savings associated with NoVOCs originate from the absence of groundwater pumps, water pipelines, and water treatment facilities. Additionally, up-front cost savings may be realized due to reduced water permitting requirements. Annual costs may be reduced over traditional remediation technologies due to energy savings resulting from the fact that groundwater is not significantly lifted above the water table; maintenance savings associated with reduced above-ground and in-well equipment; operating costs associated with chemical pretreatment and sludge management are eliminated.

The final two criteria are modifying criteria. As described in Chapter 2, the purpose of modifying criteria is to ensure that state and local issues not directly addressed in the threshold and balancing criteria are given adequate attention.

State Acceptance

This criterion is used to assess the degree to which NoVOCs addresses any policy or administrative issues that the state may have. In general, state concerns tend to be with issues similar to those addressed in other areas of the performance criteria. NoVOCs is reviewed favorably under this criterion because it is reliable, permanent, easy to implementation, cost effective, and able to meet ARARs. There has been virtually no resistance to NoVOCs based on state policy or administrative issues.

Community Acceptance

This criterion is used to measure the acceptance of NoVOCs by the local community. As in the previous criterion, community concerns tend to be with issues similar to those addressed in other areas of the performance criteria. The commercial vendors of the technology are careful to involve the public at the earliest possible stages of a remediation effort. This creates a well-informed community who almost always unanimously support the use of the technology. As discussed earlier, in the case of the MMR site, the community actually rallied around the technology for its continued operation. NoVOCs clearly meets the demands of the local community.

When asked to compare NoVOCs against the CERCLA criteria, one regulator involved with the EPA SITE program indicated that NoVOCs would be rated nearly identically to UVB technology (Simon, 1997). The EPA SITE program has completed a full-scale demonstration and evaluation of UVB. The evaluation of UVB against the CERCLA criteria presented in the EPA SITE technology evaluation report is presented in Table 4-3.

Remarks

In Chapter 2 we found that it is rarely the case that a single method of technology transfer is capable of moving a technology from full-scale demonstration to implementation. Rather, it is the combination of many methods of technology transfer working in harmony that ultimately accomplish the task. The case study of NoVOCs emphasizes this point as several different methods of technology transfer were involved in the process of transferring the technology. Interestingly, the methods were not employed solely by the technology developer but also by the commercial vendors who gained early interest in the technology. Although the commercial partners did provide momentum for the transfer of the technology, the fact that the initial steps toward the transfer of the technology must be taken by the technology developer should not be overlooked.

Table 4-3. EPA SITE Program Evaluation of UVB Against the CERCLA Criteria: Indicator of NoVOCs Evaluation Against CERCLA Criteria (U.S. EPA, 1995b:7)

CRITERION	UVB TECHNOLOGY PERFORMANCE
1. Overall Protection of Human Health and the Environment	The technology eliminates contaminants in groundwater and prevents further migration of those contaminants with minimal exposure to on-site workers and the community. Air emissions are reduced by using carbon adsorption units.
2. Compliance with Federal ARARs	Compliance with chemical-, location-, and action-specific ARARs must be determined on a site-specific basis. Compliance with chemical-specific ARARs depends on (1) treatment efficiency of the UVB system, (2) influent contaminant concentrations, and (3) the amount of treated groundwater recirculated within the system.
3. Long-Term Effectiveness and Permanence	Contaminants are permanently removed from the groundwater. Treatment residuals (for example, activated carbon) require proper off-site treatment and disposal.
4. Reduction of Toxicity, Mobility, or Volume Through Treatment	Contaminant mobility is initially increased, which facilitates the long-term remediation of the groundwater within the system's radius of influence. The movement of contaminants toward the UVB system within the system's capture zone prevents further migration of those contaminants and ultimately reduces the volume of contaminants in the groundwater.
5. Short-Term Effectiveness	During site preparation and installation of the treatment system, no adverse impacts to the community, workers, or the environment are anticipated. Short-term risks to workers, the community, and the environment are presented by increased mobility of contaminants during the initial start-up phase of the system and from the system's air stream. Adverse impacts from the air stream are mitigated by passing the emissions through carbon adsorption units before discharge to the ambient air. The time requirements for treatment using the UVB system depends on site conditions and may require several years.
6. Implementability	The site must be accessible to large trucks. The entire system requires about 100-700 square feet (average 300). Services and supplies required include a drill rig, off-gas treatment system, laboratory analysis, and electrical utilities.
7. Cost	Capital costs for installation of a single unit are estimated to be $180,000, and annual operation and maintenance costs estimated to be $72,000.
8. Community Acceptance	The small risks presented to the community along with the permanent removal of the contaminants make public acceptance of the technology likely.
9. State Acceptance	State acceptance is anticipated because the UVB system uses well-documented and widely accepted process for the removal of VOCs from groundwater and for treatment of the process air emissions. State regulatory agencies may require permits to operate the treatment system, for air emissions, and to store contaminated soil cuttings and purge water for greater than 90 days.

Note: Costs quoted in criterion #7 are for UVB system.

Without the proper initial approach to the transfer of the technology, little commercial interest would have resulted, making the ultimate transfer of the technology that much more difficult. In the case of NoVOCs, the technology developer was careful to select a member in the commercial sector capable of understanding the technical aspects of the

technology, as well as someone who would be able to gain the interest of his employer. This individual has been termed the "technology champion" in technology transfer literature (Souder *et al.*, 1990:10). As the "champion", this person directs the technology around or through the barriers to its transfer with relentless effort. The "technology champion" is most commonly in the technology-developing organization, however he need not be as illustrated through this review of NoVOCs. The technology developer was also careful to provide financial incentives to commercial entities. By patenting the technology, the technology was proprietary, providing incentive for commercial entities to obtain a license on the technology —possibly one that was exclusive. While the notion is commonly held among federal researchers that government inventions are public domain and therefore do little to encourage commercial interest in an invention, the fact is that under the Bayh-Dole Act and the Federal Technology Transfer Act government entities may grant licenses, even exclusive ones, to government developed and patented technologies to private entities. Additionally, the Federal Technology Transfer Act requires the return of royalties to the laboratories for further technology transfer activities, and to the inventors themselves (Gatchett *et al.* 1992:893) and although CRDAs most commonly lead to government ownership of a technology, the Federal Technology Transfer Act also defines methods that allow the non-government CRDA partner to obtain title to inventions developed with government support. Clearly, just the fact that a technology is patented is not sufficient to gain the interest of commercial entities. If the technology were lacking in performance, cost effectiveness, or regulatory acceptability a technology license would have little worth. In some cases, a technology that shows promise may not need to be licensable for the commercial sector to implement it

(bioventing, for example). Whatever the case, it can not be over looked that the existence of a patent and the possibility of obtaining a technology license clearly contributed to the ultimate commercialization of NoVOCs.

Full-scale demonstrations seem to have played a significant role in the transfer of NoVOCs. Nearly every interviewee conceded that without the data gathered at the Edwards AFB demonstration, the technology would have had little chance of implementation commercially. Although the demonstration at Aubange, France was insufficient for U.S. regulators and technology users, it did complement and lend credibility to the data gathered at Edwards AFB. The review of the Edwards AFB full-scale demonstration made clear the importance of a well designed and planned technology demonstration. The effect of delaying a demonstration or improperly installing a treatment system can have effects that ripple well beyond the demonstration itself. This can be seen in the case of NoVOCs, as some believe that the technology lost nearly two years in the technology transfer process due to flawed demonstration planning. The fact that a delayed demonstration can have so much impact on the transfer of an environmental remediation technology emphasizes the importance and possibly, necessity, of full-scale demonstrations of environmental remediation technologies. More discussion on full-scale technology demonstrations will be provided in the results section of this thesis.

Many initiatives focusing on the transfer of environmental remediation technologies were presented in Chapter 2. Although a SITE demonstration/evaluation of NoVOCs is

scheduled to take place during 1997, it will occur a full decade after the technology's initial conception. Due to what some interviewees explained as an unfortunate tendency of some technology evaluation initiatives to focus on the shortcomings of a technology rather than its benefits, parties involved with NoVOCs thought it best to avoid these evaluations in the early stages of the technology transfer process.

The use of news releases and magazine articles had some significance in the transfer of NoVOCs. While the importance of scientific scrutiny offered by peer reviewed journal articles can not be over looked, neither can the benefit of expedient circulation of information offered by news releases and magazine articles. EG&G Environmental and Metcalf & Eddy continue to take advantage of this media to gain NoVOCs awareness among even more people in the environmental community.

While NoVOCs does perform well against the CERCLA performance evaluation criteria, it does not perform overwhelmingly better than many other traditional or innovative technologies. For example, the contaminant is brought to the surface and may even require disposal as a concentrate in another media. This practice clearly presents an increased risk to workers over completely *in situ* treatment technologies and does little to reduce the toxicity of the contaminant. However, many technologies are currently accepted that pose the same shortcomings. While NoVOCs does not perform overwhelmingly better than other technologies when evaluated against the CERCLA criteria, it is better in small ways that give it an edge under specific contaminant and hydrogeologic scenarios. For instance, the Hanford site is contaminated with both

tritium, a non-volatile radioactive contaminant, and carbon tetrachloride, a volatile contaminant. Since NoVOCs is directed at the remediation of volatile contaminants, it can be implemented at sites such as the Hanford site with no concern of bringing radioactive waste to the surface. As another example, consider UVB technology. Although UVB technology is quite similar to NoVOCs in concept (an in-well system that recirculates groundwater), the method used to establish recirculation differs substantially. UVB uses a high vacuum applied to the wellhead to lift groundwater for air stripping inside a large diameter air-contactor. A submerged pump is often required to enhance circulation. NoVOCs, on the other hand, uses a pressurized air flow to drive both the pumping and air stripping. Only a light wellhead vacuum is used to extract stripped vapors. The NoVOCs system allows for higher flowrates, wider recirculation zones, and more effective groundwater reoxygenation than UVB –leading to lower costs and faster cleanups than UVB (Metcalf & Eddy, 1997:14). Additionally, NoVOCs allows for easy installation of a pilot well which can conclusively demonstrate whether the technology is appropriate for a site before a full-scale system is installed –and if a full-scale system is installed, the pilot well may be used as part of that system. NoVOCs also seems to gain an edge over other technologies in the criterion of cost. Technologies offering similar treatment processes to NoVOCs such as traditional air stripping must pump water to the surface requiring more energy than the air lift method employed by NoVOCs.

Conclusion

While the transfer of NoVOCs employed many of the methods of technology transfer described in the literature review (Chapter 2), simply listing these methods does not

create a recipe for successful technology transfer. It does, however, illustrate that there may be a necessity, or at least utility, to employing multiple methods. In addition to simply employing methods of technology transfer, it was important to the transfer of NoVOCs that the participants had the ability to be flexible, for instance, by responding to the lack of acceptance by U.S. regulators and technology users of data collected in France by organizing a full-scale demonstration at a U.S. site. The emergence of a technology champion was also crucial to the transfer of the technology. The continuity and foundation that this key player represented could not easily have been replaced. Even the most sophisticated management or administrative system can not avoid every pothole that may be encountered along the road of technology transfer –only a technology champion can effectively guide a technology through the barriers that almost certainly will arise.

The lessons learned from this case study will play an important role in the drawing of conclusions about the transfer of an environmental remediation technology from full-scale demonstration to implementation.

V. Results and Recommendations

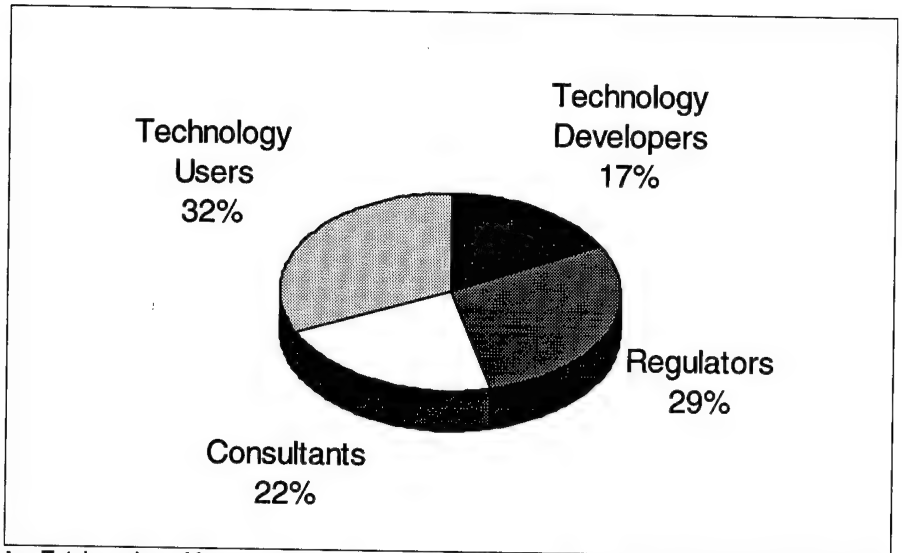
Introduction

Chapters 1 through 4 have demonstrated the many parameters that affect the success or failure of innovative environmental remediation technology transfers. It should be clear that a simple technology transfer model that promises success for every technology transfer endeavor is nonexistent –nor will it ever exist. Every transfer is composed of different key individuals trying to accomplish different goals with sometimes vastly different technologies. However, through interviewing those involved with environmental remediation technologies, researching the existing literature data base, and studying, in detail, one technology (NoVOCs) that has successfully maneuvered through the technology transfer maze, some "best practices" that aid in the transfer of an environmental remediation technology have emerged. The goal of this chapter is to present those practices and make recommendations on how best to implement them.

Explanation of Data

The methodology employed for this research, convergent methodology, utilized data from three sources: literature review, case study, and interviews. This chapter focuses on trends in environmental remediation technology transfer that were found to be, at a minimum, moderately verified (see Chapter 3 for an explanation of unverified, moderately verified, and verified data trends). While literature review data and case study data are presented in Chapters 2 and 4, respectively, interview data is presented within the sections of this results chapter. Figure 5-1 outlines the make-up of interviewees.

Figure 5-1. Percentage of Interviewees by Category



Note: Total number of formal interviews conducted within each category: Developers, 7; Regulators, 12; Consultants, 9; Users, 13. Appendix B lists the interviewees.

In order for interviewees to remain anonymous, actual interviewees are not referenced. However, statements made in this chapter will provide the reader with the percentage of interviewees supporting any claim made in these results. For example, if 8 out of the 12 regulators interviewed all indicated a certain trend, it will be presented in this chapter as "regulators (67%) indicate that…". In some cases, interviewees did not comment on a topic either because the topic was not presented during the interview or because the interviewee had no opinion on the topic. Therefore, if 80% of interviewees, for example, share a particular view, the remaining 20% do not necessarily oppose that view –they simply may not have commented on the topic.

Recommendations to Improve Environmental Remediation Technology Transfer

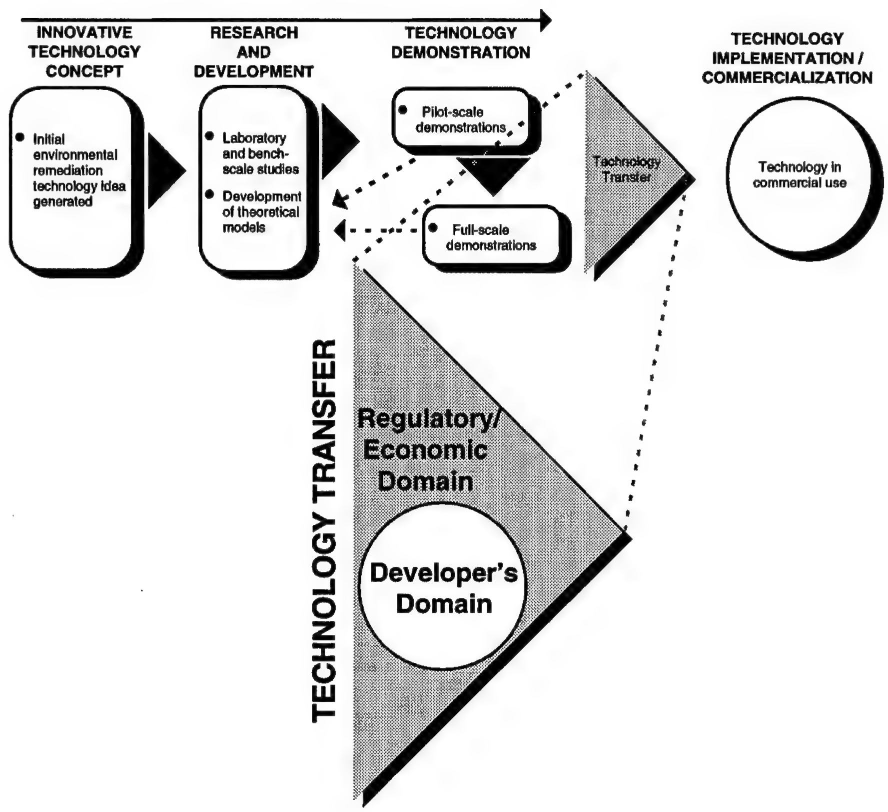
A significant finding of this research is that environmental remediation technology transfer actions can be separated into two general areas or domains. First, there is a domain that is defined and affected by legislation, regulation, economics, and policy. This domain is beyond the control of the technology developer. For example, the CERCLA process of achieving a Record of Decision or State legislation regulating the use of an injectant are part of, what we will call the regulatory/economic domain. Second, there is a domain that may be controlled or influenced by the technology developer. For example, the decision to participate in one of the technology demonstration initiatives is a decision that can be made within what we call the developer's domain. While the developer has control over technology transfer actions in his/her domain, all actions take place within the framework of the regulatory/economic domain. Figure 5-2 depicts how the two domains are related. We will use the two-domain model as a framework to make recommendations on improving environmental remediation technology transfer. After presenting the recommendations, we shall revisit the two-domain model and draw some conclusions relevant to it.

Regulatory/Economic Domain

The regulatory/economic domain technology transfer elements were defined above as those elements dictated by legislation, regulation, and policy. More broadly, tier 1 elements are those that are beyond the control of a single technology developer, technology user, consultant, or regulator. The NRC has conducted research centered on

this tier (NRC, 1997). Because the NRC research on this topic was published less than three months prior to the completion of this thesis, and because of the thoroughness of the NRC, many of their findings that are supported by this thesis are included here.

Figure 5-2. Two-Domain Technology Transfer System



Although this thesis has focused on developer domain technology transfer actions, a discussion of regulatory/economic domain findings is relevant. As depicted in figure 5-2, developer domain actions can only take place within the framework established by the regulatory/economic domain.

Stimulating the Market (Regulatory/Economic Domain)
- Verified Data Trend

The environmental remediation technology market differs from typical markets in that it lacks economic incentives to accelerate the use of innovative technologies. As presented in Chapter 2, incentives exist for site owners to delay cleanup rather than actively engage in it. This is primarily a result of a regulatory system that has minimal consequences for those who delay cleanup and strict consequences for those who engage in it. Additionally, by offering remediation contracts that operate on a cost-reimbursable basis, the public sector does little to stimulate market interest in innovative technologies.

The NRC suggests that five types of initiatives must be pursued if the environmental remediation technology market is going to shift from one that is almost completely driven by regulations to one that is driven by economic interest (NRC, 1997:61). The five initiatives are displayed in Table 5-1. Each of these initiatives will be discussed.

Table 5-1. Initiatives Needed to Shift from a System of Regulatory Drivers to Economic Drivers (NRC, 1997:61)

1.	*Creation of economic incentives*
2.	*More consistent enforcement of regulations*
3.	*More predictable regulatory process for selecting cleanup goals and remediation technologies*
4.	*Availability of information about the size and nature of all sectors of the remediation market, both public and private*
5.	*Creation of more opportunities to test innovative remediation technologies and verify their performance*

Initiative 1 –Creation of economic incentives: little economic incentive exists for site owners to actively pursue and employ innovative technologies. As described in

Chapter 2, monetary drivers usually dictate that a site owner delay cleanup rather than engage in it. This was verified in the literature review through publications that documented the costs of litigation, the most common avenue of delay (GAO, 1994c; Lee, 1995:249). The NRC suggests that one way of overcoming this barrier is to improve corporate reporting of remediation liabilities to the Securities and Exchange Commision (SEC). While a requirement already exists for disclosure of environmental liabilities in quarterly and annual reports, the regulation is not clearly written and, therefore, subject to varying interpretations by corporate accountants. A clarification of the existing regulation coupled with strict enforcement of the regulation would provide incentive for corporate site owners to cleanup, thereby eliminating the liability from their balance sheets. Because technical uncertainties clearly limit the accuracy with which environmental liability can be reported, a uniform method of cost estimation would have to be adopted among corporations (NRC, 1997:64).

Initiative 2 – More consistent enforcement of regulations: A system that has regulation as its primary driver must be consistent in the manner in which the regulations are enforced. Consider the U.S. tax system. Although the U.S. tax system is based on self-reporting, it works because there are known and enforced consequences for those who don't comply. Even with the current (at the time this thesis was written) debate on capitol hill over the problems in the Internal Revenue Service (IRS), few, if any, politicians have suggested that the IRS relax penalties for those individuals who have acted unlawfully. Enforcement of contaminated site remediation regulations should be similarly consistent. If penalties for noncompliance were strictly enforced, site owners

would engage in cleanup activities, and hence be motivated to seek out the most cost-effective remediation solutions. Furthermore, based on environmental economics, for strict enforcement of regulations to have any real consequences, the penalty for noncompliance must be more costly than the cost of cleanup.

Initiative 3 – More predictable regulatory process for selecting cleanup goals and remediation technologies: While the EPA has clearly defined the steps required for site remediation, consistency among EPA regions and, sometimes, even within regions varies greatly. Some contend that the establishment of presumptive remedies, remedies that will be the preferred choice for cleaning up different types of contaminated sites, runs "counter to innovation" and that the establishment of presumptive remedies tends to "freeze the menu of technologies at the point in time at which the presumptive remedies were developed" (NRC, 1997:66). Technology developers (86%) overwhelmingly held this view. The developers indicated that because presumptive remedies are based largely on the long-term track record of a technology, innovative technologies that inherently have short-term track records, possibly only one demonstration, have a difficult time gaining "presumptive remedy" status. In other words, without a long-term track record, a technology cannot become a presumptive remedy –without being a presumptive remedy, a technology is often overlooked and cannot establish a long-term track record. Instead of selecting presumptive remedies, consistency in the technology selection process between sites and between EPA regions needs to become a reality. This consistency should be extended to different regulatory programs as well. While the technology selection process is somewhat similar between

sites that are covered under RCRA and those that are covered under CERCLA, the process is not exactly the same –adding to the confusion of developers who aim to satisfy technology selection criteria.

Not only should the technology selection process have consistency, but it should also be controlled to a great extent by the technology user/site owner. Technology users (62%) and consultants (100%) interviewed expressed discontent with the degree to which regulators control the technology selection process. Environmental remediation technology customers must have the freedom to select any technology they desire to provide incentives for innovation. In theory, regulators should have little concern over the technology selected for implementation at a particular site, as long as that technology achieves the requirements established by the regulators. However, in reality, regulators play a leading role in technology selection.

Massachusetts has developed a program that seeks to overcome barriers to technology selection by the site owner or the site owner's consultant. Consultants in Massachusetts may apply to become "licensed site professionals." The license, which allows it's holder to approve selected remedies, is applicable to sites where remediation is required under the Massachusetts Contingency Plan. Requirements for consideration of the license include a minimum of 8 years in hazardous waste consulting, with at least 5 of those years consisting of experience as a principal decisionmaker (NRC, 1997:68). To overcome the tendency of the licensees to avoid selecting innovative technologies, Massachusetts has prepared guidance documents on innovative technologies, an on-line

data base with innovative technology performance information, and educational sessions promoting the use of innovative technologies. Additionally, regulatory incentives are provided including reduced fees during the early phases of installation and operation as well as extended deadlines. While the "licensed site professional" system is relatively new and has not had time to be perfected, it has provided certainty to the cleanup of hazardous waste sites in Massachusetts. Site owners can rest assured that if a licensed site professional selects an environmental remediation technology for implementation at their site, they can implement cleanup without fear of delays due to regulatory barriers.

An additional mechanism that has been considered that may aid in technology selection consistency is the establishment of national cleanup standards. Some assert that the establishment of national cleanup standards for groundwater would not only aid in the consistency of technology selection from site to site, but also aid the researchers developing innovative environmental remediation technologies because they would have clear performance goals (NRC, 1997:66). Neither the NRC, nor the research conducted for this thesis led to clear conclusions concerning the usefulness of national cleanup standards (44% in favor, 37% against, 19% did not comment). Interviewees who favored national standards felt that the existence of such standards would provide a greater level of consistency for developers. Additionally, national cleanup standards would aid regulators who, because of political and social reasons, sometimes select cleanup levels that vary greatly between geologically similar sites. Those in favor of national cleanup standards indicate that the existence of such standards may create an incentive to achieve higher levels of cleanup, much like the establishment of standards for drinking water has

fostered the development of improved water treatment technologies (NRC, 1997:67). Those who are against the establishment of national cleanup standards argue that the establishment of such standards would limit the professional judgment of trained professionals to determine the appropriate level of cleanup from site to site. For example, while one site may threaten the drinking water supply of a nearby community if intensive remediation efforts are not adopted, another site may offer minimal, or no, health risks to a population. Clearly the high-risk site requires cleanup to levels to relatively stringent standards. However, the low-risk site may not require the same level of remediation. The arguments suggested by both parties are well conceived. The EPA should give careful consideration to this debate when promulgating regulations.

Initiative 4 – Availability of information about the size and nature of all sectors of the remediation market, both public and private: While new technologies for environmental remediation have been and are being developed, there is some ambiguity for technology developers. Namely, there is no comprehensive data base fully disclosing the extent and nature of the nation's contaminated sites. 43% of developer interviewees expressed this concern. Requiring private companies, as well as government organizations, to fully disclose information about their known contaminated sites would provide technology developers with knowledge that would help direct their efforts (NRC, 1997:68). Additionally, the requirement would have effects similar to those of the Toxic Release Inventory (TRI) program, a program that requires companies to report toxic emissions. The TRI program, which publishes an annual list of the nation's largest polluters, has stimulated companies to reduce emissions to avoid

appearing on the list. It has also prompted environmental groups to direct their actions at companies ranking high on the list. Similar to the TRI, a requirement for companies and government organizations to fully disclose information about contaminated sites would provide incentive for site-owners to cleanup rather than the alternative –delay, as delays could lead to public scrutiny and boycotts.

Initiative 5 – Creation of more opportunities to test innovative remediation technologies and verify their performance: Corporations are reluctant to be the first to use an innovative environmental remediation technology. The high cost of cleanup usually lowers interest in an environmental remediation technology that does not have a track record. To move technologies to complete implementation in the commercial sector, and hence, make them a viable option for employment at government installations, more opportunities must be created for full-scale testing of the technologies prior to introducing them to the market.

The existence of more demonstration and verification programs could stimulate the market for innovative technologies by providing the needed cost and performance data required by site owners and regulators. However, problems exist in the current technology demonstration and verification initiatives that need to be addressed if the creation of additional demonstration initiatives is to positively impact the technology transfer process. The creation of additional and reorganization of existing technology demonstration and verification programs is another regulatory/economic domain action that warrants discussion.

Technology Demonstration and Verification Initiatives (Regulatory/Economic Domain)
- Moderately Verified Data Trend

While the EPA and other organizations have developed initiatives (covered in Chapter 2) for environmental remediation technology testing at government facilities owned by DOD, DOE, and others, the initiatives are somewhat poorly coordinated with each other and do not have universal acceptance (U.S. Small Business Administration, 1994:9). The limited standardization of cost and performance data among the demonstration initiatives has led to confusion among stakeholders seeking to interpret the data. Developer interviewees (57%) indicated that because the demonstration initiatives are sponsored by different agencies, many times cost and performance data collected through the demonstration is only accepted by those agencies participating in the initiative. While as many test facilities as possible should be encouraged, the way to overcome coordination and data acceptance barriers may be to establish one center of all verification programs. This center would serve to coordinate performance and cost reporting as well as compile a national data base of the results gathered during the demonstration projects. Three possible organizations have been suggested that could serve as the center of the verification program (NRC 1997:225).

1) *EPA*: The EPA SITE program could be greatly expanded to serve as the center of the verification program.

2) *Third-party franchise*: A third-party center (under the direction of a private testing organization or professional association) could work with technology developers and function as the center of the verification program. This center would evaluate results of the demonstration and submit a verification report to the EPA.

3) *Nonprofit research institute*: A nonprofit research institute affiliated with a university could establish technology evaluation protocols. It could franchise other laboratories to assist with the testing who would submit results to the institute for verification.

As mentioned above, sometimes agencies are reluctant to accept information generated through demonstration projects sponsored by other agencies –public or private. In addition to establishing a center to coordinate all of the verification programs, initiatives made up of members from both the public and private sectors should be established to encourage sharing and acceptance of data generated by the demonstration initiatives. 66% of interviewees shared this view. Presented in Chapter 2, the Remediation Technologies Development Forum (RTDF) is an example of an initiative that has attempted to employ this strategy. RTDF is composed of EPA, Government organizations, and industry. Although the program has not been in existence long enough to draw conclusions about the strategy, member organizations hope that the efforts will lead to early acceptance and implementation of innovative technologies because three of the major stakeholders (technology users, developers, and regulators) are involved.

In addition to being poorly coordinated, existing initiatives do not have the capacity to demonstrate the many innovative technologies. For instance, the Applied Advanced Technology Demonstration Facility (AATDF, presented in Chapter 2) received 170 applicants for demonstration under the program in its first year of operation (1993). Of the 170 applicants, the program only had the capacity to accept 12 (NRC, 1997:216). The EPA must consider establishing additional sites to demonstrate innovative environmental remediation technologies.

Even if a technology is demonstrated to perform well, there is still no guarantee that the technology will be implemented. There are some programs, however, that offer ways to overcome this barrier. For example, the Navy's Environmental Leadership Program has a policy that promises full-scale implementation at a minimum of one site for any environmental remediation technology successfully demonstrated under the program (EPA, 1996a). This system was praised by many technology developer interviewees (86%) who agreed that too many times an innovative environmental remediation technology is shown to perform well yet does not get implemented by the government agency demonstrating it. Review of the literature also revealed the paradox (GAO, 1994a). Clearly, providing assurance that a successfully demonstrated technology would be employed is a measure that if adopted would be welcomed among technology developers who are striving to transfer their technology to the commercial sector.

The above discussion focused on proposals to improve demonstration and verification that are within the regulatory/economic domain. There are also proposals for technology demonstration and verification initiatives that are within the technology developer's domain which will be presented later in this chapter.

World Wide Web Applications (Regulatory/Economic Domain)
- Moderately Verified Data Trend

The advent of the World Wide Web has increased the capacity for information sharing beyond anything imagined thirty years ago when the United States was beginning to recognize the consequences of improper disposal of hazardous waste. One method of utilizing this information tool is through the establishment of a data base containing

information on environmental remediation technologies. Many interviewees, especially consultants (78%), indicated difficulty in finding a comprehensive resource outlining innovative environmental remediation technologies in a way that was easy to understand yet detailed enough to have value. While some data bases already exist, such as VISITT and ReOpt discussed in Chapter 2, these data bases are not widely disseminated and have no standard format for data presentation. A comprehensive data base could be established on the internet allowing information about environmental remediation technologies to be easily accessed. The data base should have a consistent framework for data entry so that technologies contained in the data base could be easily compared.

Development of Template Sites (Regulatory/Economic Domain)
- Moderately Verified Data Trend

The establishment of a comprehensive data base on the internet would solve the need identified by interviewees (44%) for a sort of "one-stop shop" for environmental remediation technologies. As indicated above, to have value, the data base would need a consistent framework around which the performance data could be displayed. The NRC suggests the use of "template sites" as part of this framework (NRC, 1997:15). The template sites, which could be developed by EPA or some other working group, would represent the range of conditions typical at most sites. Once the template sites are developed, technology users could require that cost and performance data be reported relative to the template sites. This, like the establishment of a comprehensive data base, would ease the burden of the technology user as well as environmental regulators attempting to compare alternative environmental remediation technologies. An example of what the template sites may look like after their development is provided in table 5-2.

Table 5-2. Example Template Sites (NRC, 1997:236)

Template Number	Depth to Water Table (m)	Aquifer Thickness (m)	Hydraulic Conductivity	Groundwater Flow Rate (m/year)
1	*4.6 (15 ft)*	*7.6 (25 ft)*	*5.0 x 10^{-4} cm/sec*	*3 (10 ft/yr)*
2	*4.6 (15 ft)*	*7.6 (25 ft)*	*2.5 x 10^{-2} cm/sec*	*150 (500 ft/yr)*
3	*4.6 (15 ft)*	*21 (70 ft)*	*5.0 x 10^{-4} cm/sec*	*3 (10 ft/yr)*
4	*4.6 (15 ft)*	*21 (70 ft)*	*2.5 x 10^{-2} cm/sec*	*150 (500 ft/yr)*
5	*30 (100 ft)*	*7.6 (25 ft)*	*5.0 x 10^{-4} cm/sec*	*3 (10 ft/yr)*
6	*30 (100 ft)*	*7.6 (25 ft)*	*2.5 x 10^{-2} cm/sec*	*150 (500 ft/yr)*
7	*30 (100 ft)*	*21 (70 ft)*	*5.0 x 10^{-4} cm/sec*	*3 (10 ft/yr)*
8	*30 (100 ft)*	*21 (70 ft)*	*2.5 x 10^{-2} cm/sec*	*150 (500 ft/yr)*

Note: Soil porosity is assumed to be 25 percent, and hydraulic gradient is assumed to be 0.005 cm/cm for all eight cases.

The actions within the regulatory/economic domain discussed so far have been applicable to both the public and private sectors. There exists, however, some regulatory/economic domain actions that are exclusive to the public sector. These actions are reviewed below.

Cooperative Research and Development Agreements -CRDAs (Regulatory/Economic Domain)
- Verified Data Trend

The Federal Technology Transfer Act (FTTA, presented in Chapter 2) gave federal laboratories and research facilities the authority to enter into CRDAs. A CRDA is an agreement that provides a written and legal framework for collaborative efforts between federal laboratories and private sector cooperators (a detailed explanation of a CRDA is presented in Chapter 2). Developer interviewees (43%) from both the public and private sectors indicated that the process of obtaining a CRDA is inefficient, often leading one or both parties to abandon the process of obtaining such an agreement. The literature review supports this claim. For instance, Carr (1992a:13) indicates that "a number of industrial partners complain that current delays for approving CRDAs and, particularly, funds for laboratory R&D efforts are too long for the CRDA process to be of value". Chapman

(1989:11) suggests that "burdensome or time-consuming procedures inhibit the successful negotiation of cooperative research and development agreements". Private sector developer interviewees were particularly concerned with the temporal short-comings of the inefficient process. 60% (3 of the 5 private-sector developers interviewed) pointed out the importance of seizing temporal advantage with new technologies due to proprietary considerations.

While both private and public sector interviewees view the establishment of CRDAs under the FTTA as a positive action, both also suggest that improvements to the process should be made for it to be of any real value. Improvements would not necessarily involve additional legislation, but rather would likely occur within the federal agencies and private sector cooperators seeking to exploit the use of CRDAs. One way of overcoming the barriers presented by CRDAs would be to establish streamlined guidelines for the implementation of a CRDA. If properly written, the guidelines could be used by government laboratories, regardless of specialty, as a standardized procedure. A working group composed of public sector agencies and private sector cooperators could be created to compose the guidelines. There would likely be a need for three different sets of guidelines depending on the objective of a given CRDA. One set would be written to give rights to any technologies developed during the cooperative research to the government, while a second set would give rights to the private sector cooperator. A third set would allow for shared rights.

While the rights to any technologies developed under a CRDA must be considered, the value of the rights to an environmental remediation technology is a topic of considerable debate. This topic will be discussed later in this chapter under developer domain actions.

Technology Patents and Private-Sector Research Partners (Regulatory/Economic Domain)
- Verified Data Trend

The case study on NoVOCs revealed that the primary developer of the technology was careful to patent the technology before accepting any government funds so that the technology would be proprietary rather than public-domain. The belief that the use of government funds in a research project mandates that the research product be non-proprietary is widespread. The literature revealed a GAO study (1988:3) where potential research cooperators in the private-sector (in all technology fields, including environmental remediation) were interviewed. Two-thirds of the officials interviewed in the course of the study held the opinion that "unless a business pays all of the costs, the research is non-proprietary and the public...can get access to research results through the Freedom of Information Act." Indeed, this belief was almost universally accepted among public and private-sector researchers (86%) contacted for the purpose of this thesis. The fact is, however, that while the extent to which proprietary information made available by a cooperating company (or developer) may be protected varies from agency to agency, it varies based solely upon how willing the agency is to protect the research. The Federal Technology Transfer Act (presented in Chapter 2) set up provisions for the protection of proprietary information. The Savannah River Site (SRS), used for the development and testing of environmental remediation technologies, offers an example where government

funds are involved, yet proprietary information is being retained by a private sector firm. SRS is owned by the DOE and operated by Westinghouse, a private-sector company. While Westinghouse is intimately involved with the development and demonstration of innovative environmental remediation technologies at SRS, much of the funding is provided by DOE. Since negotiating an agreement that would allow Westinghouse to retain the rights to some technologies developed at SRS in 1993, Westinghouse has retained rights to seven technologies.

Even when private-sector developers are aware of the possibility of keeping research proprietary, the bureaucratic difficulties associated with information protection are often cumbersome. For instance, while the FTTA established provisions for developers to retain proprietary information, Westinghouse still had to negotiate extensively with DOE to establish clear guidelines on how the provisions would be instituted. The establishment of streamlined CRDA guidelines suggested above may overcome this barrier. The fact remains, however, that most technology developers are operating under the assumption that the involvement of government funds precludes proprietary research. The government should make clear to prospective cooperators that research conducted in a cooperative arrangement can remain proprietary. This will stimulate private-sector firms to establish cooperative agreements with the government –possibly setting up a technology pull atmosphere for environmental remediation technologies developed through the cooperative agreement. Furthermore, private-sector firms obtaining proprietary rights to the technology would be motivated to implement the technology to gain revenue.

Government Policy on Remediation Contracts (Regulatory/Economic Domain)
- Moderately Verified Data Trend

Mentioned earlier, the government often awards environmental remediation contracts on a cost-reimbursable basis –providing no incentive for remediation contractors to explore cost-effective alternatives for site cleanup. This practice was confirmed through government technology user interviewees knowledgeable of environmental contracts. Most interviewees (75% or 6 of the 8 government technology users interviewed) felt that a fixed-price contract, while having some problems that would have to be overcome, would cut cleanup costs dramatically. The literature also offers reason for concern over the current cost-reimbursable method. For instance, the GAO found evidence of fraud, waste, and abuse by government environmental remediation contractors due to inadequate oversight of the contractors (GAO, 1995b). By awarding contracts on a cost-reimbursable basis and offering little oversight of the contractors performing cleanup actions, the government is failing to provide stimulus to the environmental remediation technology market. If the government hopes to reap the benefits of resources spent on research and development of new and innovative environmental remediation technologies, it should begin awarding cleanup contracts based on a fixed-cost basis.

Simply switching to a fixed-cost contract will not be as easy as it may sound. One question that will need to be answered is how to decide whether additional payment is justified due to situations where sub-surface anomalies are missed during site characterization or other unforeseen problems arise. One way of addressing this problem as well as providing more contractor oversight could be through the establishment of an

independent peer review panel (NRC 1997:65). The panel would assure that remediation efforts are proceeding toward scheduled milestones and could also review requests for cost-increases to determine if they are technically justified. The Air Force's Air Education and Training and Material Commands have peer review panels in place that review proposed remedies for the remediation of contaminated sites at bases in those commands. These panels' responsibilities could be expanded to incorporate the suggestions above and serve as a model for other government agencies.

Summary of Suggested Regulatory/Economic Domain Actions

The framework established within the regulatory/economic domain defines the boundaries for the developer's actions –possibly making the regulatory/economic domain somewhat more important than the domain of the developer. It is within the regulatory/economic domain that major changes can be made to improve how environmental remediation technologies are transferred.

Many suggested changes to the regulatory/economic domain have been proposed in this chapter that may aid in the transfer of innovative environmental remediation technologies. Actions to stimulate the environmental technology market would provide incentive for site owners and regulators to seek out cost-effective alternatives to traditional remedies. The establishment of an environmental remediation technology data base on the internet would provide a comprehensive collection of environmental remediation technologies presented in a way that is easily accessed and detailed enough to have value. Development of clearer ways to compare cost and performance data for

alternative technologies, such as the use of template sites, would make clear the financial and temporal benefits of selecting an innovative environmental remediation technology. Public-sector actions suggested in this chapter include switching from cost-reimbursible environmental remediation contracts to fixed-price contracts and the development of streamlined guidelines for the establishment of CRDAs. Additionally, making known the fact that research can remain proprietary even when government funds are involved should encourage private-sector companies to pursue CRDAs.

As presented in the introduction to this chapter, there is a second technology transfer domain, the domain controlled or influenced by the technology developer. Recommendations within this domain are presented below.

Technology Developer's Domain

Full-Scale Technology Demonstrations (Developer Domain)
- Verified Data Trend

Nothing was more overwhelmingly asserted by interviewees (93%) and the literature (Griener, 1996; Gierke and Powers, 1997; Fountain, 1997) than the efficacy of full-scale technology demonstrations. However, while the importance of technology demonstrations is widely recognized, what performance data researchers should collect during those demonstrations is an issue of considerable debate. The NRC (1997:11) suggests that technology developers should seek to provide data that conclusively answers two questions:

1) *"Does the technology reduce risks posed by the soil or groundwater contamination?"*

2) *"How does the technology work in reducing those risks? That is, what is the evidence proving that the technology was the cause of the observed risk reduction?"*

The four criteria used to describe the ability of a technology to reduce risks posed by the contamination (question #1) are: (1) Reduction in contaminant mass; (2) Reduction in contaminant concentration; (3) Reduction in contaminant mobility; (4) Reduction in contaminant toxicity (NRC, 1997:175). Demonstrating that the technology is able to achieve all four criteria is not necessary, and likely not ever the case for most environmental remediation technologies. Rather, a well performed technology demonstration should be able to provide data that conclusively links the implementation of the technology to an observed success in decreasing one or more of the four risk measures, thereby also satisfying question #2. Table 5-3 lists data that may be used to establish cause and effect relationships between an environmental remediation technology and an observed risk reduction as defined by the four criteria listed above.

The demonstration of a single piece of evidence listed in Table 5-3 alone is usually not sufficient. Regulator interviewees (75%) contended that the case for a remediation technology's performance is enhanced when the body of evidence supporting it is large, preferably containing more than one of the indicators listed in Table 5-3.

Although the overwhelming majority of full-scale technology demonstrations have been conducted scientifically and have led to conclusive results (especially those technologies

that have participated in the demonstration initiatives), some regulator interviewees (33%) cautioned that conclusions researchers draw are sometimes suspect. To adequately carry out demonstrations that clearly demonstrate the evidence listed in Table 5-3, experimental controls will almost always have to be employed. Without proper controls, it will likely be impossible to prove whether a contaminant reduction in mass, concentration, toxicity, or mobility is the result of the remediation technology or of some other cause. Table 5-4 lists some experimental controls that are typically employed during full-scale technology demonstrations.

Once the two questions presented earlier are conclusively answered, developers should seek to report their findings –in terms of both performance and cost.

Peer Reviewed Literature (Developer Domain)
- Verified Data Trend

Many mechanisms of information dissemination are available and were discussed in Chapter 2. Interviewees from all groups expressed satisfaction with magazine articles (66%), internet postings (78%), and fact sheets (46%) because of their expediency and availability. The literature review as well as the case study of NoVOCs also supports the use of these media. The one element that such media lack, however, is the scientific scrutiny only offered through the peer review process. Regulators (92%), especially, touted the importance of publications in peer reviewed journals outlining full-scale demonstration findings. These publications offer evidence that the scientific community agrees with and supports conclusions drawn through the full-scale technology demonstration. For the publications (either peer reviewed or otherwise) to be of

Table 5-3. Data to Establish Cause-and-Effect Relationship Between Technology and Remediation (after NRC, 1997:193)

Stabilization/Solidification /Containment Technologies	Biological Reaction Technologies	Chemical Reaction Technologies	Separation/Mobilization/ Extraction Technologies

• **Mechanism for decreased leachability**
• Formation of insoluble precipitate
• Strong sorption/bonding to solids
• Vitrification, cementing, encapsulation
 	
• **Integrity of stabilized material**
• Completeness of process throughout treatment region
• Compressive strength of solidified material
• Reaction to weathering, e.g., wet/dry and freeze/thaw tests
• Reaction to changes in groundwater chemistry
• Microstructural analyses of composition
 	
• **Geochemical conditions that affect leachability of stabilized materials (pH, Eh, competing ions, complexing agents, organic liquids, etc.)**
• Increased ratio of immobile to mobile phase contaminants
• Fluid transport properties of solidified material
    • Permeability
    • Porosity
    • Hydraulic gradient across monolith
    • Rate water flow through monolith
 	
• **Indicators of liquid/gas flow field consistent with technology (i.e., indication that flow through the stabilized or contained region is blocked)**
	• Stoichiometry and mass balance between reactants and products
	• Increased concentrations of intermediate stage and final products
	• Increased ratio of transformation product to reactant
	• Decreased ratio of reactant to inert tracer (or, in general, decreased ratio of transformable to nontransformable substances)
	• Increased ratio of transformation product to inert tracer (or, in general, increased ratio of transformation product to nontransformable substances)
	• Relative rates of transformation for different contaminants consistent with laboratory data
	• Increased number of bacteria in treatment zone
	• Increased number of protozoa in treatment zone
	• Increased inorganic carbon concentration
	• Changes in carbon isotope rations (or, in general, in stable isotopes consistent with biological process)
	• Decreased electron acceptor concentration
	• Increased rates of bacterial activity in treatment zone
	• Bacterial adaptation to contaminant in treatment zone
	• Indicators of liquid/gas flow field consistent with technology (i.e., indication that treatment fluids have been successfully delivered to the contaminated area)
		• Stoichiometry and mass balance between reactants and products
		• Increased concentrations of transformation products
		• Increased concentrations of intermediate stage products
		• Increased ratio of transformation product to reactant
		• Decreased ratio of reactant to inert tracer (or, in general, decreased ratio of transformable to nontransformable substances)
		• Increased ratio of transformation product to inert tracer (or, in general, increased ratio of transformation product to nontransformable substances)
		• Relative rates of transformation for different contaminants consistent with laboratory data
		• Changes in geochemical conditions, consistent with treatment reactions (pH, Eh, etc.)
		• Indicators of liquid/gas flow field consistent with technology (i.e., indication that treatment fluids have been successfully delivered to the contaminated area)
			• Increased concentrations (mass) of contaminant in outflow stream
			• Decreasing mass of contaminants remaining in subsurface consistent with mass extracted in outflow stream
			• Increased mass removal per unit volume of transport or carrier fluid
			• Increased ratio of contaminants in carrier fluid to aqueous-phase contaminants
			• Increased ratio of contaminants in carrier fluid to non aqueous phase contaminants
			• Observed movement of injected carrier fluids (flushing amendments or injected gases) or of tracers in carrier fluids
			• Spatial distribution of contaminants prior to, during, and after remediation
			• Indicators of liquid/gas flow field consistent with technology

Table 5-4. Experimental Controls for Improving Technology Evaluation (NRC, 1997:194)

Method	Purpose
Collection of baseline data	Collection of baseline data is the most basic type of experimental control and is essential to the success of the technology test. Without excellent baseline data, it will not be possible to develop an accurate comparison of conditions before and after application of the technology.
Controlled Contaminant Injection	In controlled contaminant injection, groundwater from the site is spiked with the contaminants under consideration and re-injected into the aquifer. Therefore, the initial makeup, mass, location, and distribution of contaminants in the subsurface are known. Under these controlled conditions, the contaminant can be more easily and accurately tracked and monitored to determine the effect of the remediation technology.
Conservative tracers	Conservative tracers do not undergo the reactions associated with *in situ* reactive technologies. However, they are subject to a number of nonreactive processes that affect flow paths, flow rates, mixing, and retention of contaminants. Therefore, conservative tracers can be used to distinguish remediation resulting from the treatment process from that which occurs naturally.
Partitioning Tracers	Partitioning tracers provide an indication of the total mass and spatial distribution of nonaqueous-phase liquids (NAPLs). They can be used to compare NAPL mass and spatial distribution prior to technology application with NAPL mass and distribution after remediation. Thus, they allow evaluation of NAPL removal and spatial patterns using a nondestructive technique.
Sequential start-and-stop testing	By alternating technology application and resting periods, the contaminant's fate can be observed under both natural conditions and remedial conditions. In this way, the effects of the technology can be separated from remediation caused by naturally occurring processes. In addition, the start-and-stop approach can be used to distinguish between dynamic and equilibrium processes.
Side-by-side and sequential application of technologies	Side-by-side testing of two or more technologies at one site can be used to compare the capabilities of different technologies for the same hydrogeologic and contaminant setting. As an alternative, technologies can be applied sequentially at the same site to determine the marginal effectiveness of one technology over another.
Untreated Controls	Untreated controls can help distinguish between technology-enhanced remediation and intrinsic remediation that occurs as a result of naturally occurring processes. The use of untreated controls is analogous to side-by-side testing with one of the remediation technologies being intrinsic remediation.
Systematic variation of technology's control parameters	The effect of changes in a technology's operating conditions on remediation can be determined by systematically changing control parameters. Ideally, this approach would be used to identify a technology's optimal operating conditions.

maximum value, some guidelines for the reporting of performance and cost data should be considered.

Cost and Performance Reporting (Developer Domain)
- Verified Data Trend

As described in the previous section on technology demonstrations, developers should be able to show conclusively that the technology reduces risk and should be able to give evidence of how that risk was reduced. A case study conducted on the transfer of one remediation technology, bioventing, concluded that documentation of scientific issues was vital to the transfer of the technology (Griener, 1996:69). Demonstrating that the technology reduces risk and providing evidence of how that risk was reduced is accomplished by collecting and analyzing at least two types of data to establish the cause and effect relationship between risk reduction and the technology (Table 5-3). Also the experimental controls (Table 5-4) used should be included in the report to prove that the technology is responsible for risk reduction. Shown in Figure 5-3, the NRC provides an example, based on *in situ* mixed-region vapor stripping in low-permeability media, of how this data may be reported and displayed.

Figure 5-3. Example of Data Reporting that Addresses the Two Fundamental Questions of Risk Reduction and Cause-and-Effect Relationship (NRC, 1997:200)

Proving *In Situ* mixed-Region Vapor Stripping in Low-Permeability Media at the Portsmouth Gaseous Diffusion Plant, Ohio

Researchers from Oak Ridge National Laboratory, Michigan Technological University, and Martin Marietta Energy Systems, Inc., conducted a full-scale field experiment to demonstrate the removal of volitile organic compounds (VOCs) from dense, low-permeability soils (West *et al.*, 1995; Siegrist *et al.*, 1995). The demonstration site, at a Department of Energy gaseous diffusion plant in Portsmouth, Ohio, had been used as a disposal site for waste oils and solvents. The silty clay deposits beneath the site were contaminated with VOCs at concentrations ranging up to 100 mg/kg. In addition, the shallow groundwater was contaminated with trichloroethylene (TCE) at concentrations above the drinking water standard.

The remediation process, termed mixed-region vapor stripping (MRVS), mixes the soils in place using rotating augers. Compressed gases are injected into the mixed soils, and the VOCs are stripped from the subsurface. The off gases are captured at the surface and treated. The study included a set of replicated tests to evaluate the relative efficiencies of ambient and heated air for stripping VOCs. The table below describes the types of data that were collected to (1) document *in situ* stripping of VOCs from the dense, low-permeability layers and (2) establish the cause-and-effect relationship between the MRVS process and the documented remediation. A conservative tracer and systematic variation of operating parameters (heat) were used as controls.

Data Objective	Type of Data
Documented reduction in VOCs	• Reduction in soil VOC concentrations • Reduction in VOC mass in soils determined by analysis of off gases • Rate of VOC mass reduction determined from analysis of off gases
Link VOC reductions to *in situ* stripping	• TCE, 1,1,1-trichloroethane, and 1,1-dichloroethylene were present at same ratios in both off gas and soil matrix • Soil, air and off-gas temperature increased concurrent with injection of heated air • Absence of soil vapor pressure and temperature changes in undisturbed soil surrounding mixing zone, suggesting VOCs in mixing zone were removed rather than forced into surrounding soils • Tracer studies revealing that the process did not homogenize the soil and caused limited translocation of soil, suggesting that the VOCs in the mixing zone were removed rather than redistributed

In addition to reporting data that links the reduction in risk to the technology, cost data should also be reported. Consultants (67%) and regulators (83%) complained of an inadequate body of cost data to compare alternative remediation technologies. Input from consultants (67%), technology users (62%), and regulators (83%) suggested that a standardized method of calculating and reporting cost data should be established. Once calculated, costs could be reported relative to the template sites presented earlier.

The public-sector has taken the lead in establishing standardized cost reporting with guidelines developed by the Federal Remediation Technologies Roundtable (FRTR, presented in Chapter 2). These guidelines, however, are to be used for the documentation of cost data relevant to on-going or completed remediation projects –not for the purpose of documenting costs of demonstration projects. Costs for demonstrations are commonly much greater than costs for actual remediation projects due to increased monitoring requirements. Therefore, while the FRTR guidelines will help determine the most cost effective currently accepted remediation technologies, they do not help to transfer innovative environmental remediation technologies. The FRTR suggests that although the guidelines were not designed as a way for technology developers to report cost data, they could be used for that purpose (FRTR, 1995:19). This would lead to a mechanism for comparing cost data for traditional and innovative environmental remediation technologies. Interviewees (20%) who were familiar with the guidelines (only 8 interviewees were sufficiently familiar with the guidelines to comment) indicated that the guidelines were ideal for accounting purposes if accurately followed. However, because the guidelines are based on a work breakdown structure (WBS), their level of detail is intense, making it difficult to use as a technology cost screening mechanism. Still, the FRTR has developed the most appropriate, well-thought out method of compiling remediation cost data thus far. The FRTR method should be used as a starting point for the establishment of more appropriate guidelines.

Herricksen and Booth (1995) offer a consolidated list of cost elements that seem reasonable to consider when establishing technology cost. These cost elements, which may be more useful that the intensive data required by the WBS, are displayed in Table 5-5.

A basic knowledge of engineering economics should make it clear that when reporting cost data based on the cost elements listed in Table 5-5, developers should explicitly state their assumptions about interest rates and project life (NRC, 1997:242). However, even when assumptions are clearly defined, interviewees reported (78% Consultants, 75% Regulators, 92% Users, 71% Developers), it is still often difficult to directly compare alternative technologies. For instance, an annual cost of remediation based on a 50 year project life can not be directly compared to a technology that reports an annual cost based on a project life of 20 years. Developers should be sensitive to the burden placed on technology users (site owners), consultants, and regulators when cost data are reported in terms that are difficult to compare. To aid the technology user, developers should devise a method of tailoring the cost data to the users needs. One way of doing this through interactive computer software is presented in a case study of *in situ* aerobic cometabolic bioremediation found in Appendix C.

Table 5-5. Typical Cost Categories Used to Compile or Estimate Costs (Herriksen and Booth, 1995)

Capital Costs	Operating Costs
Site Preparation • Site clearing • Site Access • Borehole drilling • Permits/licenses • Fencing • Heat, gas, electricity, and water to install system Structures • Buildings • Platforms • Equipment structures • Equipment shed/warehouse Process equipment and appurtenances • Cost of technology parts and supplies • Materials and supplies to make technology operative Non-process equipment • Office and administrative equipment • Data processing/ Computer equipment • Safety equipment • Vehicles Utilities • Plumbing, heating, light, security, and vent equipment Labor • Direct labor necessary to acquire, mobilize, and install system • Supervisory and administrative labor to acquire, mobilize, and install system • Design and engineering Other • Rental of commercial equipment to mobilize and install system • Start-up and testing	Direct Labor • Direct labor to operate equipment • Direct labor supervision • Payroll expenses (FICA, vacation, worker medical insurance, pension contribution) • Contract labor • Maintenance direct labor Direct Materials • Consumable supplies • Process materials and chemicals • Utilities • Fuels • Replacement parts Overhead • Plant and equipment maintenance • Liability insurance • Shipping charges • Equipment rental for operations • Vehicle supplies and insurance • Transportation • Licensing General and Administrative • Administrative labor • Marketing • Communications • Project management • Travel expenses • Interest expenses Site Management • Maintenance contract for equipment • Waste disposal • Health and safety requirements • Contract services • Site closure activities • Analytical services • Demobilization • Regulatory reporting

Once cost data is compiled, some suggested general rules of thumb for reporting it are (NRC 1997:250):

1) *"Costs of remediation technologies should be reported as cost per unit volume of the contaminated matrix treated, removed, or contained and as cost per unit mass of each specific contaminant removed, treated, or contained."*

2) *"Cost estimates should include one-time start-up costs as well as the up-and-running cost of using the technology."*

Patents and Licenses (Developer domain)
- Moderately Verified Data Trend

Although patents were discussed within the regulatory/economic domain, the discussion did not focus on the benefits of obtaining a patent in the context of expediting technology transfer. The answer to the question of whether or not a patent is useful in transferring an environmental remediation technology to full-scale implementation seems to depend upon the circumstances surrounding that technology. In the case of NoVOCs, there existed a private-sector firm, ICF Kaiser Engineers, early in the development of the technology who was interested in obtaining rights to implement the technology. Patenting NoVOCs was clearly a wise decision because it provided financial incentive for the private-sector firm to pursue the technology. Additionally, after earning rights to implement the technology, ICF Kaiser Engineers and other firms who later obtained technology licenses helped publicize the technology –relieving the technology developer of the burden to do so. Others contest, however, that obtaining a patent discourages private-sector firms from utilizing the technology. Reasons cited include the tendency of technology users to seek out technologies that are widely implemented by many different environmental contractors so that "technology shopping" for the best value can be conducted –the idea that competition is good for the buyer. A second reason that patents may not be beneficial to the transfer of innovative environmental remediation

technologies is that many firms requiring remediation services leave the decision of technology selection up to their consultant. The tendency to leave the decision up to the consultant is a criticism that the government in particular has received (GAO, 1994a:5). Consulting firms are unlikely to suggest a technology that is owned or licensed to another firm and sacrifice profits that could be made if the technology user were to employ a technology that the consulting firm could implement in-house. A final reason that technology patents may hinder the transfer of an innovative environmental remediation technology is based on the public perception of a patented technology. While in some cases a patent may lead the public to believe that the technology is technically capable (simply because it received a patent), other times it may lead the public to question whether all information about the technology is freely shared –the idea that some information may be held from the public to protect proprietary interests (NRC, 1997:180). Discussed in Chapter 2, the way the local community views a technology and the degree to which the public trusts that all information about that technology is openly communicated can oftentimes determine the fate of that technology.

Without regard to whether or not a patent can aid in the transfer of innovative environmental remediation technologies, technology developer interviewees (57%) asserted that there are difficulties enforcing patents on environmental remediation technologies. While a patent on a particular "widget", such as an innovative groundwater well design, may be easily enforced, a patent on a process is much more difficult to enforce.

Based on the information gathered in this thesis, it seems most appropriate that patents on environmental remediation technologies only be pursued when there is an interested private-sector firm motivated by financial incentive. Otherwise, patents seem to do nothing more than discourage the transfer of environmental remediation technology.

Technology Demonstration and Evaluation Initiatives (Developer domain)
- Moderately Verified Data Trend

The regulatory/economic domain actions relevant to technology demonstrations were covered earlier in this chapter. Other considerations exist within the domain of the technology developer and are presented below.

A claim emerged among technology developers (43%) purporting that many times the technology demonstration initiatives, particularly EPA's SITE program, tend to focus on the negative aspects of a demonstrated technology in evaluation reports rather than provide an unbiased report identifying both the negative as well as the positive aspects of the technology. These interviewees suggested that participation in one of the demonstration initiatives could actually be detrimental to the transfer of an innovative environmental remediation technology. An EPA SITE program employee contacted indicated that great measures are taken to ensure the preparation of unbiased technology evaluation reports. Additionally, developers (29%) assert that demonstration initiatives are often inefficient and slow to act, sometimes starting as late as two years after the scheduled start date. This, in fact, has been the case with a planned demonstration of NoVOCs under the SITE initiative (Simon, 1997). Whatever the case may be, for the majority of technology developers, the point is moot. Without the resources provided by

the demonstration initiatives and their sponsors, most technologies would never be demonstrated at full-scale –and as indicated earlier, there is nearly universal agreement on the necessity of full-scale technology demonstrations in transferring innovative environmental remediation technologies.

Developers and members of the technology demonstration initiatives need to recognize the potentially adversarial relationship that may be emerging between the two groups and seek to overcome their differences. Developers should aim to be more involved in the actual process of writing the evaluation report to make certain that both positive and negative aspects of the technology are discussed –demonstration initiatives should embrace developer involvement. Additionally, developers should work to become more involved with the actual demonstration, helping to initiate the demonstration in a timely manner –and again, demonstration initiatives should embrace increased developer involvement.

World Wide Web (Developer Domain)
- Verified Data Trend

Technology developers should realize that while peer reviewed literature provides the ultimate test of scientific validity, many people including consultants (100%), technology users (85%), and environmental regulators (83%), turn to the internet as a way of becoming educated on environmental remediation technologies. In fact, many technology users (31% –36% of those included in the 85% above) indicated that as much as 50% of what they know about remediation technologies has been learned through the internet. It is vital to the transfer of an environmental remediation technology that information about

that technology be easily accessible on the internet. The establishment of a comprehensive data base located on the internet, as suggested earlier in this chapter, would ensure that information posted there is easily accessible and readily comparable. Until such a data base exists, developers should seek to use the data bases currently available on the internet such as that established by the National Technology Transfer Center (presented in Chapter 2). Additionally, information should be posted on the developing organizations web site and any other relevant sites. NoVOCs information, for example, can be accessed through Stanford University's, the developing organization's, web site, as well as through the web sites of those firms that licensed the technology.

Technology Champion (Developer Domain)
- Verified Data Trend

The final, and clearly most important recommendation within the technology developer's domain, is the requirement for a technology champion. Without a technology champion, there is very little hope that an innovative technology will be expediently transferred. The technology champion is that individual who has the skills and willingness to lead a technology through the transfer barriers. Technology transfer literature has formally recognized the importance of the technology champion (Griener, 1996:86; Souder *et al.*, 1990:10) as did the NoVOCs case study –and while few interviewees knew such a term existed, many of them (Developers 86%, Regulators 42%, Consultants 78%, Users 69%) related the importance of such a person in moving a technology to the commercial sector. This conclusion agrees with research conducted that considered the transfer of general environmental technologies (Griener, 1996:86). Some attributes of technology champions described by interviewees are listed in Table 5-6.

Table 5-6. Technology Champion Attributes

Attribute	Qualities of Attribute
Technical Knowledge	• Technology process knowledge • Geology knowledge • Contaminant chemistry / physics knowledge (contaminant fate and transport) • Knowledge of environmental laws pertinent to the technology process and contaminants for which the technology was developed
Interpersonal Skills	• Ability to convey knowledge describing the technology in a clear, understandable fashion • Likable • Ability to establish good working relationships with key players (regulators, technology users, etc.)
Management Skills	• Organized • Motivated • Ability to network with technology users, consultants, and regulators • Ability to distribute pertinent information quickly • Knowledge of relevant environmental processes (application to demonstration initiatives, RI/FS, etc.)

Seldom is the technology champion recognized formally among technology developers and the point of this discussion is not to suggest that there should be such recognition. The important thing for developers to realize is that even though an innovative environmental remediation technology may be capable of reducing costs and cleanup times over a traditional technology, that is not enough to guarantee its transfer. There must be a member of the technology development team who makes a mission of transferring the technology.

Summary of Suggested Developer Domain Actions

The recommendations within the technology developer's domain that were discussed above represent those that were most clearly recognized during research for this thesis. That is not to say that there are no other recommendations that could be made. For

instance, reporting on technologies in magazines may be useful in the transfer of environmental remediation technologies. This research, however, found only some evidence that this may be the case and therefore publicizing the technology in magazine articles was not recommended in these results. Those actions that emerged as being clearly relevant and important for environmental remediation technology transfer were covered. Technology demonstrations have universal acceptance within the environmental community. Publication of results and findings in peer reviewed journals has nearly the same level of acceptance. These journals offer an important quality check, scientific scrutiny, that is valued particularly among regulators and consultants. While the world wide web lacks scientific scrutiny, it offers an expedient way to present information about environmental technologies to a large audience. The way cost and performance data is reported can have ramifications on the ease or difficulty of transferring an environmental remediation technology. This chapter presented some best practices for reporting this data. The efficacy of patents is somewhat determined by the circumstances surrounding a particular technology. It was suggested in this chapter that patents on environmental remediation technologies may only be worth pursuing if there will be clear financial incentive for an interested private-sector firm. Technology demonstration and evaluation initiatives provide an important service to technology developers as well as regulators, consultants, and users. To ensure that the initiatives are operated fairly and efficiently, technology developers should seek to involve themselves in both the full-scale technology demonstration and the preparation of the evaluation report –this may be an appropriate action for the technology champion. The technology champion, while not always formally recognized, drives a technology to full-scale commercialization and

implementation. It is this individual who gives the extra effort when others give up –the champion is vital, if not absolutely necessary, to environmental remediation technology transfer.

Table 5-7 presents a consolidated list of the results and recommendations outlined in this chapter. Additionally, the table indicates the data sources which verified the findings.

The two-domain system of environmental remediation technology transfer has served as the framework for our discussion of results and recommendations. However, the finding that a two-domain system exists also has significance. As depicted in Figure 5-2, the regulatory/economic domain encompasses the developer domain. This depiction represents a finding that technology transfer actions taken in the regulatory/economic domain have increased consequences over those that are categorized in the developer domain. For instance, while an action in the developer domain such as proper reporting of cost data may have utility, this action is inconsequential if the market for environmental remediation technology is not stimulated (a regulatory/economic domain action). It is therefore concluded that developer domain actions are necessary for the transfer of an environmental remediation technology but are not sufficient. For significant advancements in the transfer of environmental remediation technologies, action in the regulatory/economic communities fostering technology transfer is necessary.

Table 5-7. Sources of Trend Verification for Results / Recommendations

RESULT / RECOMMENDATION	SOURCE OF VERIFICATION
Regulatory/Economic Domain	
Environmental remediation technology market stimulation • *Verified Data Trend*	• Literature Review • Interviews • Case Study
Technology Demonstration and Verification Initiatives • *Moderately verified data trend*	• Literature Review • Case Study
World Wide Web Applications • *Moderately verified data trend*	• Literature Review • Interviews
Development of Template Sites • *Moderately verified data trend*	• Literature Review • Interviews
Cooperative Research and Development Agreements -CRDAs • *Verified data trend*	• Literature Review • Interviews • Case Study
Technology Patents and Private-Sector Research Partners • *Verified data trend*	• Literature Review • Interviews • Case Study
Government Policy on Remediation Contracts • *Moderately Verified data trend*	• Literature Review • Interviews
Developer Domain	
Full-Scale Technology Demonstrations • *Verified data trend*	• Literature Review • Interviews • Case Study
Peer Reviewed Literature • *Verified data trend*	• Literature Review • Interviews • Case Study
Cost and Performance Reporting • *Verified data trend*	• Literature Review • Interviews • Case Study
Patents and Licenses • *Moderately verified data trend*	• Interviews • Case Study
Technology Demonstration and Evaluation Initiatives • *Moderately verified data trend*	• Interviews • Case Study
World Wide Web • *Verified data trend*	• Literature Review • Interviews • Case Study
Technology Champion • *Verified data trend*	• Literature Review • Interviews • Case Study

Conclusion

This chapter has defined those technology transfer actions that have emerged as, at a minimum, modified trends. They include both policy recommendations, such as the establishment and use of template sites for cost and performance reporting, and best practices, such as how to report technology performance.

The following chapter offers a consolidated list of the results reported in this chapter as well as suggestions for further research pertinent to the transfer of environmental remediation technologies. In Appendix C of this thesis, these results are applied to one technology, *in situ* aerobic cometabolic bioremediation, and suggested actions for its transfer are offered.

VI. Summary

Introduction

Chapter 5 detailed the results of the research conducted for this thesis. This chapter summarizes those results. The findings reported in this chapter are detailed in Chapter 5. In addition to the summary of findings offered in this chapter, suggestions for further research in the field of environmental remediation technology transfer are presented.

Summary of Findings

Environmental remediation technology transfer may be affected on two levels. One level, the so-called regulatory/economic domain, encompasses elements that are beyond the control of a single technology developer, technology user, consultant, or regulator. The second level, considered the developer's domain, encompasses elements that can be controlled or influenced by the technology developer. Of course, actions in the developer's domain can only occur within the overall regulatory/economic framework. The existence of two distinct domains leads to the finding that while it is necessary for technology developers to perform technology transfer actions categorized in the developer domain, these actions are not sufficient for the transfer of environmental remediation technologies. It is the technology transfer actions that are categorized in the regulatory/economic domain that have the ability to significantly impact the transfer of an environmental remediation technology. Figure 5-2 depicts the two domains of environmental remediation technology transfer.

Recommended Actions Within the Regulatory/Economic Domain to Stimulate Technology Transfer

Environmental remediation technology market stimulation - ***Verified data trend***

- The environmental remediation technology market lacks the necessary economic incentives required to accelerate the use of innovative technologies. The current regulatory/economic system provides incentives for site owners to delay cleanup rather than engage in it. Five initiatives are suggested that will overcome this barrier to technology transfer.

1) **Create economic incentives -** Corporate reporting of remediation liabilities to the SEC should be clarified and strictly enforced. A clarification, coupled with strict enforcement, would provide incentive for corporate site owners to cleanup, thereby eliminating the liability from their balance sheets.
2) **Impose consistent enforcement of regulations -** Penalties for noncompliance with environmental regulation should be significant and strictly enforced. Consistent enforcement of regulation will lead site owners to cleanup, and hence be motivated to seek out cost effective solutions.
3) **Make regulatory processes for selecting cleanup goals and remediation technologies more predictable -** Rather than establishing presumptive remedies, consistency in the technology selection and cleanup goal-setting process between sites and EPA

regions should be encouraged. This will allow consultants and site owners the ability to make reasonable predictions about the probability of regulatory approval for the use of an innovative technology.

4) **Make information about the size and nature of all sectors of the remediation market available -** Information about the size and nature of cleanup needs should be made public so that technology developers can be well informed and make better decisions about where to concentrate their efforts. Additionally, this initiative would have effects similar to those of the Toxic Release Inventory program, providing incentive for site owners to engage in remediation.

5) **Create more opportunities to test innovative remediation technologies and verify their performance -** Technology demonstration and verification programs collect needed cost and performance data on innovative environmental remediation technologies. However, they have no standardized way of reporting cost and performance data and it is difficult for developers to gain entry to the programs. Without clear cost and performance data on an innovative technology, there is little incentive for consultants, site owners, and regulators to consider use of that technology. More opportunities should be provided so technology developers can gather this critical data.

Create one demonstration and verification facility that acts as the center for all demonstration and verification initiatives - ***Moderately verified data trend***

- While many test facilities should be made available, one test facility should serve as coordinator for all of the facilities. This will overcome currently existing coordination problems between the demonstration initiatives as well as serve to overcome barriers to data acceptance by an organization not directly associated with the particular demonstration initiative. Three possible types of organizations could serve as the center:

1) *EPA*: The EPA SITE program could be greatly expanded to serve as the center of the verification program.

2) *Third-party franchise*: A third-party center (under the direction of a private testing organization or professional association) could work with technology developers and function as the center of the verification program. This center would evaluate results of the demonstration and submit a verification report to the EPA.

3) *Nonprofit research institute*: A nonprofit research institute affiliated with a university could establish technology evaluation protocols. It could franchise other laboratories to assist with the testing who would submit results to the institute for verification.

Develop a comprehensive environmental technology data base on the internet - ***Moderately verified data trend***

- One comprehensive data base providing information about environmental remediation technologies should be developed and made accessible on the internet. The data base should include cost and performance data on the technologies in a format that allows easy comparison of technologies.

Develop template sites for reporting cost and performance data - *Moderately verified data trend*

- The development of template sites (see Table 5-2) would provide a framework for reporting cost and performance data. This would ease the burden of technology users, consultants, and regulators attempting to compare alternative environmental remediation technologies.

Develop streamlined guidelines for the establishment of CRDAs - *Verified data trend*

- The provision set up by the FTTA for government laboratories to enter into CRDAs is not being fully exploited due to inefficiencies in the process of obtaining such an agreement. Because CRDAs foster a technology-pull environment (see Chapter 2), which favors technology transfer, streamlined guidelines should be developed to take full advantage of the agreements.

Encourage cooperative research agreements between the government and private-sector firms by making known to the private-sector firm that research may remain proprietary - *Verified data trend*

- Private-sector firms are often discouraged from entering into research agreements with the government because of a widely held view that the research can not legally remain proprietary. The FTTA, however, set up provisions to protect proprietary information. Government laboratories should seek to better inform possible cooperators on their rights to retain proprietary research, thus encouraging more cooperative research agreements.

Government policy on remediation contracts should be changed from contracts that are awarded on a cost-reimbursable basis to contracts awarded on a fixed-price basis - *Moderately verified data trend*

- The government often awards environmental remediation contracts on a cost-reimbursable basis –providing no incentive for remediation contractors to explore cost-effective alternatives for cleanup. To overcome this barrier, the government should start awarding environmental remediation contracts on a fixed-cost basis.
- To address situations where sub-surface anomalies are missed during site characterization or other unforeseen problems arise, a peer review panel could be established to determine if additional payment is justified. By reviewing the contractors ability to meet scheduled cleanup milestones, this panel would also provide contractor oversight, something that has been identified as a problem with government cleanups.

Recommended Actions Within the Developer Domain to Stimulate Technology Transfer

Developers should seek to answer two primary questions during full-scale technology demonstrations - *Verified data trend*

- The efficacy of full-scale technology demonstrations is widely recognized. Technology developers should seek to gather data during the demonstrations that can conclusively answer two questions:

1) *"Does the technology reduce risks posed by the soil or groundwater contamination?"*

2) *"How does the technology work in reducing those risks? That is, what is the evidence proving that the technology was the cause of the observed risk reduction?"* (NRC, 1997:11)

- Risk reduction (question #1)is defined as : (1) Reduction in contaminant mass; (2) Reduction in contaminant concentration; (3) Reduction in contaminant mobility; (4) Reduction in contaminant toxicity (NRC, 1997:175). Developers should demonstrate at least one of these four reductions.
- To link an observed risk reduction to the environmental remediation technology (question #2), developers should establish a cause-and-effect relationship between the technology and the observed risk reduction. Table 5-3 lists data that may be used to establish this cause-and-effect relationship.

Technology developers should publish findings in peer reviewed literature - *Verified data trend*

- Technology developers should publish research results in peer reviewed literature. Peer reviewed literature offers scientific scrutiny that is not found in other information dissemination media. For the publications to be of maximum value, some guidelines for the reporting of performance and cost data should be considered. These guidelines are presented below.

Cost and performance data should be reported in standardized methods - ***Verified data trend***

- Technology developers should publish in peer reviewed literature at least two types of data collected to establish the cause-and-effect relationship between risk reduction and the technology. Experimental controls (Table 5-4) used should also be outlined. An example of how this data may be reported is provided in Figure 5-3.
- Developers should seek to provide cost data in a way that allows comparison of alternative technologies. The use of template sites should overcome this barrier. Additionally, developers should explicitly state cost assumptions including interest rate, and project life. When reporting cost data in peer reviewed literature, developers should follow two general rules:

  1) *"Costs of remediation technologies should be reported as cost per unit volume of the contaminated matrix treated, removed, or contained and as cost per unit mass of each specific contaminant removed, treated, or contained."*

  2) *"Cost estimates should include one-time start-up costs as well as the up-and-running cost of using the technology." (NRC, 1997:250)*

Patents on environmental remediation technologies should only be pursued when doing so would provide financial incentive for a private-sector firm - ***Moderately verified data trend***

- Patents on environmental remediation technologies should only be pursued when there is an interested private-sector firm motivated by financial

incentive. Otherwise, patents seem to do nothing more than discourage the transfer of environmental remediation technology.

- Reasons that patents may hinder the transfer of an environmental remediation technology include:
    - Technology users tend to seek out technologies that are widely implemented by many different environmental contractors so that "technology shopping" for the best value can be conducted –the idea that competition is good for the buyer.
    - Many firms requiring remediation services leave the decision of technology selection up to their consultant. Consulting firms are unlikely to suggest a technology that is owned by another firm and sacrifice profits that could be made if the technology user were to employ a technology that the consulting firm could implement in-house.
    - The existence of a technology patent may lead the public to question whether all information about the technology is freely shared –the idea that some information may be held from the public to protect proprietary interests (NRC, 1997:180). The way the local community views a technology and the degree to which the public trusts that all information about that technology is openly communicated can oftentimes determine the fate of that technology.

Technology developers should seek to work more closely with the demonstration and evaluation initiatives to ensure timely demonstrations and fair evaluation reports - ***Moderately verified data trend***

- While there is a growing belief among technology developers that some of the demonstration and evaluation initiatives are inefficient and emphasize the negative aspects of technologies, without the initiatives many technologies would not be tested at all. Developers should aim to be more involved in the actual process of writing the evaluation report to make certain that both positive and negative aspects of the technology are documented – demonstration initiatives should embrace developer involvement. Additionally, developers should try to become involved with the actual demonstration, helping to initiate the demonstration in a timely manner – again, demonstration initiatives should embrace developer involvement.

Technology developers should seek to educate technology users, consultants, and regulators by offering technology information on the internet - ***Verified data trend***

- While peer reviewed literature offers scientific scrutiny, many technology users, consultants, and regulators are turning to the internet for expedient information. The establishment of a national data base, suggested earlier in this chapter, would be a useful tool for these groups. Until such a data base is established, technology developers should seek to use data bases already available on the internet. Additionally, developers should post information about their technology on the developing organization's web site.

A technology champion is crucial to the ultimate transfer of an environmental remediation technology - *Verified data trend*

- Even though an innovative environmental remediation technology may be capable of reducing costs and cleanup times over a traditional technology, that is not enough to guarantee its transfer. There must be a member of the technology team, the technology champion, who makes a mission of transferring the technology. Some common attributes of technology champions are presented in Table 5-6.

Suggestions for Future Research

This thesis has reported on some of the broad changes and best practices that are needed to overcome barriers to environmental remediation technology transfer. To institute some of these practices, however, more detailed research should be conducted on the individual findings. Additional research needs include:

World Wide Web Data Base

The benefits of a comprehensive data base that would provide performance and cost data on remediation technologies have been presented in this thesis. However, research is needed to develop the proper format of such a data base to ensure its usability and value to technology users, consultants, and regulators.

Template Sites for Reporting Cost and Performance Data

The NRC has developed example template sites to be used when reporting cost and performance data (Table 5-2). However, these templates are "first cut" suggestions. Extensive research is needed to create template sites that are able to address the wide range of site conditions and contaminants that exist while assuring that technologies can easily be compared using the template sites.

Guidelines for Establishing CRDAs

The use of streamlined guidelines for the establishment of CRDAs should enhance environmental technology transfer. Research should be conducted to identify the major problems with the current system of establishing CRDAs and recommend a streamlined system. Additionally, this research could review the reasons why private-sector cooperators are often unable to retain proprietary research and offer suggestions to make the process easier.

Information Dissemination

This thesis concludes that peer reviewed literature and internet postings are valuable information disseminators. Detailed research focusing on all of the information dissemination mechanisms (presented in table 2-5) should be conducted to determine the efficacy of each method and to make recommendations concerning the circumstances under which each method is most applicable.

Technology Champion

This thesis presents the conclusion that technology champions are vital to the transfer of an environmental remediation technology. While the technology champion is rarely a defined position on a research team, research should be conducted to determine if such a defined position would be valuable. Additionally, further research could evaluate whether currently existing technology transfer centers should tie a single employee to each technology rather than assigning work groups to multiple technologies as is the current practice.

Evaluation of Suggested Actions for the Transfer of *In Situ* Aerobic Cometabolic Bioremediation

Appendix C offers suggestions based on this thesis for the transfer of *in situ* aerobic cometabolic bioremediation. After some, or all, of these suggestions have been applied to the technology, a case study of the technology could be performed. The case study would be a useful tool to evaluate the recommendations made in this thesis and add to the environmental remediation technology transfer knowledge base.

Conclusion

This research was conducted pursuant to two goals:

1) To identify the barriers to transferring an environmental remediation technology from field evaluation to implementation, as well as the elements necessary to overcome those barriers, in order to apply the technology to remediate DoD contaminated sites.

2) To present *in situ* aerobic cometabolic bioremediation as an example of an innovative technology currently being evaluated in the field in order to demonstrate strategies and techniques that may be useful in transitioning the technology to full-scale implementation.

The first goal conclusions are presented in Chapter 5 and in summary format in this chapter. These conclusions focused on transferring innovative environmental remediation technologies to the commercial sector. Without transferring these technologies to the commercial sector, there is no possibility of implementing the technologies at DOD contaminated sites.

Appendix C applies the findings presented thus far to one technology, *in situ* aerobic cometabolic bioremediation, in order to accomplish the second goal of this thesis.

APPENDIX A
INTERVIEW GUIDE

Interviewee General Information

<table>
<tr><td>NAME</td><td>DATE OF INTERVIEW:

TIME OF INTERVIEW:</td></tr>
<tr><td>TITLE</td><td rowspan="2">CATEGORY
Technology Developer
Technology User
Consultant
Environmental Regulator</td></tr>
<tr><td>ORGANIZATION</td></tr>
<tr><td>TELEPHONE NUMBER</td><td rowspan="3">MAILING ADDRESS</td></tr>
<tr><td>EMAIL ADDRESS</td></tr>
<tr><td>FAX NUMBER</td></tr>
<tr><td colspan="2">ADDITIONAL RELEVANT INFORMATION</td></tr>
</table>

ENVIRONMENTAL REMEDIATION TECHNOLOGY TRANSFER INTERVIEW GUIDE

I. General Topics (for discussion with each respondent category)

1. BARRIERS TO ENVIRONMENTAL REMEDIATION TECHNOLOGY TRANSFER

a. Which of these barriers do you think significantly affect the transfer of environmental remediation technology?

- **Management Barriers** *(Risk Aversion, Desire to Expedite Cleanup, Desire to Maintain Projected Budget)*
- **Institutional Barriers** *(Regulatory Standards, Permitting Procedures)*

b. Are there additional barriers you can identify?

2. METHODS OF ENVIRONMENTAL REMEDIATION TECHNOLGY TRANSFER

a. Which of the following methods of technology transfer do you think are the most successful?

- *Patents and Licensing, CRDAs / Cooperative Research, Employee Exchange, Full-Scale Technology Demonstrations, Technology developer incentives, Use of Intermediaries, Internet (WWWeb) Information Dissemination, Peer-Reviewed Journal Information Dissemination, Trade Journal Information Dissemination, Conferences, Reports, etc.*

b. Information Dissemination Methods - Which ones have the most utility?

a. Active Methods *(Broker Organizations, Workshops, Seminars, or Conferences, Information Centers, Education)*

b. Passive Methods *(Mailings, Technical Reports, News Releases, Journal and Magazine Articles, Fact Sheets, Videotapes, Decision Tools, Electronic Bulletin Boards)*

I. General Topics (continued)

3. FULL-SCALE TECHNOLOGY DEMONSTRATIONS

a. *Can you provide any information on the usefulness of full-scale technology demonstrations as a method of environmental remediation technology transfer?*

b. *Have you ever been involved with a full-scale environmental remediation technology demonstration? If so, please elaborate.*

4. ADDITIONAL SPACE - *if needed*

ENVIRONMENTAL REMEDIATION TECHNOLOGY TRANSFER INTERVIEW GUIDE

II. TECHNOLOGY DEVELOPER-specific topics/questions

1.	**MARKET PULL / TECHNOLOGY PUSH / MODIFIED TECHNOLOGY PUSH**
a.	*Perspectives on what is really happening from the technology developer's point of view.*
2.	**CERCLA PERFORMANCE EVALUATION CRITERIA**
a.	*How are the CERCLA performance evaluation criteria viewed by a technology developer?*
b.	*From the technology developer's perspective, which of the balancing criteria are the most crucial to the implementation of an environmental remediation technology?*
3.	**FULL SCALE TECHNOLOGY DEMONSTRATIONS**
a.	*Have you ever conducted or been involved in a full-scale technology demonstration?* Yes No
b.	*Do you think technology demonstrations are important to the transfer of an environmental remediation technology?*
c.	*What kinds of data are most important to gather during a technology demonstration? (What kinds of data do you think technology users and environmental regulators are interested in?)*

II. TECHNOLOGY DEVELOPER-specific topics/questions (continued)

4. PATENTS

a. Do you see any utility in using patents to transfer environmental remediation technology?

b. Can you identify any instances where patents have been used effectively in the transfer of environmental remediation technology?

5. TECHNOLOGY DEVELOPER INCENTIVES

a. In particular, what incentives for technology developers do you think are most successful in increasing the desire to transfer technology?

6. EMPLOYEE EXCHANGES

a. Have you ever been involved in a employee-exchange program?

Yes

No

b. If so, in what ways can this experience be used to facilitate environmental remediation technology transfer?

c. Are you aware of any instances in which a government employee worked in a private firm through an employee-exchange program? If so, please explain.

INTERVIEW GUIDE

III. TECHNOLOGY USER-specific topics/questions

1. MARKET PULL / TECHNOLOGY PUSH / MODIFIED TECHNOLOGY PUSH
a. *Perspectives on what is really happening from the technology user's point of view.*
2. INNOVATIVE ENVIRONMENTAL REMEDIATION TECHNOLOGY USE
a. *What tools are available for technology users to keep abreast of new and innovative technologies?*
b. *What types of tools would you like to see available that would help you keep abreast of new and innovative technologies?*
c. *What types and degree of information/data do you require before you are willing to look into the use of an innovative technology at a site?*
3. CERCLA PERFORMANCE EVALUATION CRITERIA
a. *How are the CERCLA performance evaluation criteria viewed by a technology user?*
b. *From the technology user's perspective, which of the balancing criteria are the most crucial to the implementation of an environmental remediation technology?*

III. TECHNOLOGY USER-specific topics/questions (continued)

CERCLA Performance Evaluation Criteria (continued)

c. With regards to the CERCLA performance evaluation criteria, is your work load increased at all when attempting to justify the use of an innovative environmental remediation technology?

4. TECHNOLOGY SELECTION CASE STUDY - ***the following questions should be answered based upon one particular site***

a. How did you ultimately choose a technology (for a particular site)? --What criteria were used?

b. Have you ever chosen an innovative technology? If yes, how did you decide upon it?

c. If you answered yes to part b, how did you find out about the innovative technology?

5. FULL SCALE TECHNOLOGY DEMONSTRATIONS

a. Have you ever conducted or been involved in a full-scale technology demonstration?

Yes

No

b. Do you think technology demonstrations are important to the transfer of an environmental remediation technology?

c. What kinds of data are most important to gather during a technology demonstration? (What kinds of data do you think technology developers should be gathering during full-scale demonstrations?)

III. TECHNOLOGY USER - specific topics/questions (continued)

6. PATENTS

a. Do you see any utility in using patents or licenses to transfer environmental remediation technology?

b. Can you identify any instances where patents have been used effectively in the transfer of environmental remediation technology?

7. TECHNOLOGY USER INCENTIVES

a. In particular, what incentives for technology users do you think are most successful in increasing the desire to implement an innovative technology?

ENVIRONMENTAL REMEDIATION TECHNOLOGY TRANSFER
INTERVIEW GUIDE

IV. CONSULTANT-specific topics/questions

1.	**INNOVATIVE ENVIRONMENTAL REMEDIATION TECHNOLOGY USE**
a.	*What tools are available for consultants to keep abreast of new and innovative technologies?*
b.	*What types of tools would you like to see available that would help you keep abreast of new and innovative technologies?*
c.	*What types and degree of information/data do you require before you are willing to recommend the use of an innovative technology at a site?*
2.	**TECHNOLOGY RECOMMENDATION CASE STUDY**
a.	*Have you ever recommended use of an innovative technology?*
b.	*What factors were important in deciding to recommend use of the innovative technology (how did you come up with the recommendation)?*
c.	*How did you hear about the innovative technology?*
d.	*How did the client react to your recommendation (did the client readily accept your recommendation or did you have to convince the client that the technology would perform adequately)?*

IV. CONSULTANT-specific topics/questions (continued)

3. TECHNOLOGY SELECTION RECOMMENDATION	
a.	*How important are the CERCLA performance evaluation criteria to technology recommendation?*
b.	*With regards to the CERCLA performance evaluation criteria, is your work load increased at all when attempting to justify the use of an innovative environmental remediation technology?*
c.	*In your opinion, which of the following are most important when recommending a technology: 1) Regulation; 2) Economics; 3) Public Relations; 4) Process Technology*

4. FULL SCALE TECHNOLOGY DEMONSTRATIONS	
a.	*Have you ever been involved in a full-scale technology demonstration?* Yes No
b.	*Do you think technology demonstrations are important to the transfer of an environmental remediation technology?*
c.	*What kinds of data are most important to gather during a technology demonstration? (What kinds of data do you think technology developers should be gathering during full-scale demonstrations?)*

IV. CONSULTANT-specific topics/questions (continued)

5. CONSULTANT INCENTIVES / DISINCENTIVES

a. What, if any, incentives exist for consultants to explore and recommend innovative cleanup technologies?

b. What, if any, disincentives exist for consultants to explore and recommend innovative cleanup technologies.

6. CLIENTELE

a. Are there any general truisms with regard to clientele relevant to the transfer of environmental remediation technologis? (For example: Large companies/site owners tend to be more receptive to the use of an innovative cleanup technology)

V. ENVIRONMENTAL REGULATOR-specific topics/questions

1. INNOVATIVE ENVIRONMENTAL REMEDIATION TECHNOLOGY USE
a. What types and degree of information/data do you require before you are willing to permit the use of an innovative technology at a site?
b. What types of tools would you like to see available that would help you keep abreast of new and innovative technologies?

2. CERCLA PERFORMANCE EVALUATION CRITERIA
a. How important are the CERCLA performance evaluation criteria to the environmental regulator's job?
b. How important is it that a technology fully satisfy the criteria?
c. Which of the nine criterion are most important to an environmental regulator? *1. Overall protection of human health and the environment* *2. Compliance with (ARARs)* *3. Long-term effectiveness and permanence* *4. Reduction of toxicity, mobility, or volume through treatment* *5. Short-term effectiveness* *6. Implementability* *7. Cost* *8. State acceptance* *9. Community acceptance*

V. ENVIRONMENTAL REGULATOR-specific topics/questions (continued)

3. FULL SCALE TECHNOLOGY DEMONSTRATIONS
a. Have you ever overseen a full-scale technology demonstration? Yes

No

b. *Do you think technology demonstrations are important to the transfer of an environmental remediation technology?*

c. *What kinds of data are most important to gather during a technology demonstration? (What kinds of data do you think technology developers should be gathering to prove a technologies effectiveness?)*

4. REGULATORY PROCEDURES

a. *In what ways do regulatory procedures and processes help the transfer of an innovative environmental remediation technology? In what ways do they hinder it?*

5. REGULATOR INCENTIVES

a. *What incentives exist for regulators to use innovative technologies at their sites? What disincentives exist?*

APPENDIX B
LIST OF INTERVIEWEES

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APPENDIX C

In Situ Aerobic Cometabolic Bioremediation

Introduction

The second thesis objective presented in Chapter 1 is:

- To present *in situ* aerobic cometabolic bioremediation as an example of an innovative technology currently being evaluated in the field in order to demonstrate strategies and techniques that may be useful in transitioning the technology to full-scale implementation.

This appendix provides an overview of *in situ* aerobic cometabolic bioremediation and reviews the technology as it progressed through the development stages from initial conception to the present knowledge base. Also, *in situ* aerobic cometabolic bioremediation will be evaluated using the CERCLA performance criteria. Finally, based upon the results of this thesis, recommendations will be presented that should aid in the transfer of this technology.

Overview

In situ aerobic cometabolic bioremediation is an environmental remediation technology that is primarily focused on the cleanup of groundwater contaminated with chlorinated aliphatic hydrocarbons (CAHs). The technology uses indigenous microorganisms at a contaminated site to destroy dissolved contaminant. Using this technology, the cleanup process occurs *in situ,* or in place. No contaminated groundwater is pumped to the surface, negating the need for costly disposal of hazardous waste. The process is cometabolic, meaning the indigenous microorganisms, while oxidizing one chemical compound (the primary substrate) for energy and growth, produce an enzyme which

fortuitously degrades the target contaminant. The enzyme produced by the microorganisms to oxidize the primary substrate is a protein-like substance that acts as a catalyst for the degradation of the contaminant. Contaminant degradation provides no benefit to the microorganism (McCarty and Semprini, 1993:265). Figure C-1 shows a conceptual depiction of the technology in plan view. Figures 7-2 and 7-3 display methods of implementing the technology based on site geology.

Technology Progression

As presented in Chapter 1, TCE was widely used as a solvent and in recent years has been recognized as a major groundwater contaminant. In 1985, Wilson and Wilson first demonstrated cometabolism of TCE in soil columns through the addition of natural gas (the primary substrate) and oxygen as the electron acceptor to stimulate the growth of indigenous microorganisms (Wilson and Wilson, 1985). Their findings have led to widespread interest in the potential of *in situ* cometabolism for the degradation of TCE and other CAHs (Hopkins and McCarty, 1995:1628).

Figure C-1. *In Situ* Aerobic Cometabolic Bioremediation - Concept

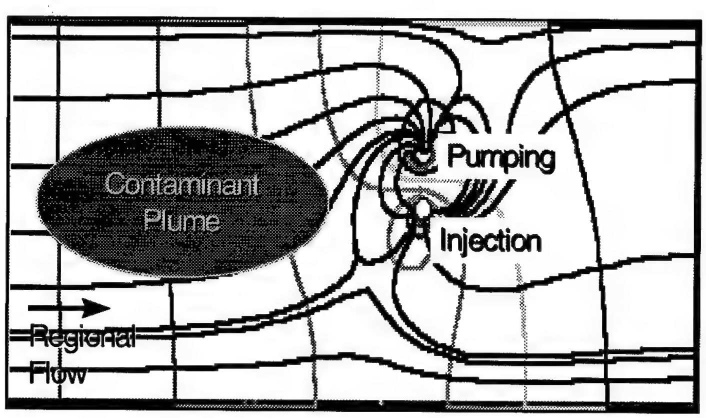
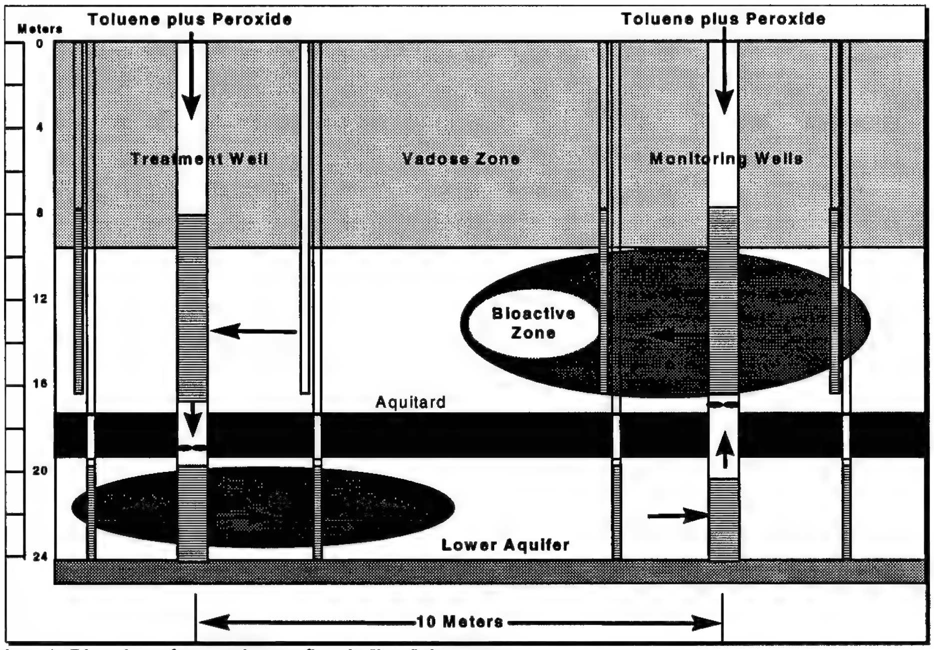
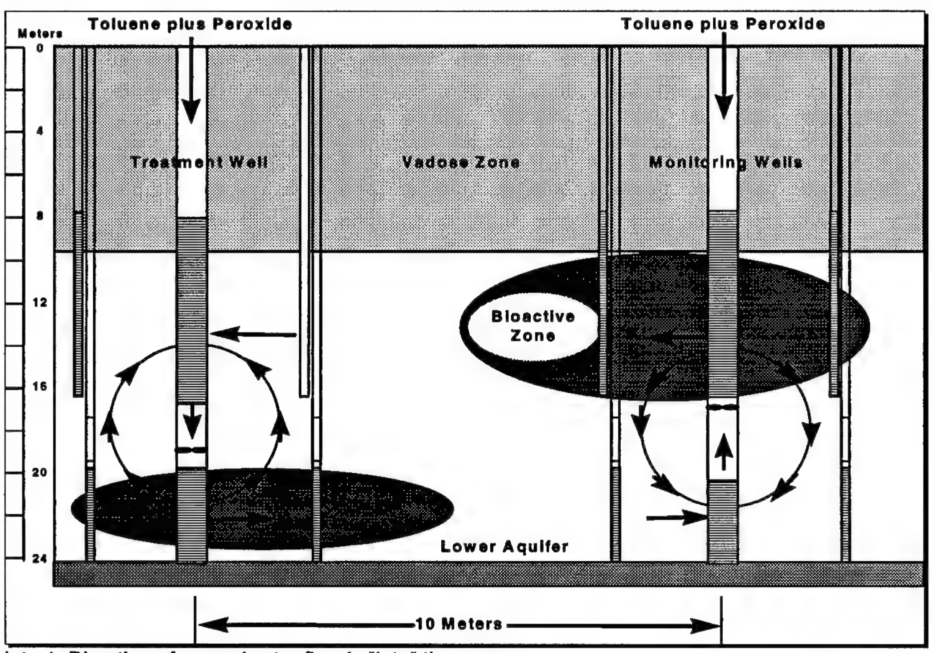


Figure C-2. *In Situ* Aerobic Cometabolic Bioremediation - Implementation Scheme #1



Note 1: Direction of groundwater flow is "into" the page.
Note 2: This figure represents a site that has an impermeable layer present. Highly anisotropic conditions can use this design.

Figure C-3. *In Situ* Aerobic Cometabolic Bioremediation - Implementation Scheme #2



Note 1: Direction of groundwater flow is "into" the page.
Note 2: This figure represents a site that does not have an impermeable layer present and is not anisotropic. Some short-circuiting may occur between screens in a single well.

The first field studies to evaluate the efficacy of *in situ* aerobic cometabolic bioremediation were conducted at the Moffett Federal Airfield (formerly the Moffett Naval Air Station) in Mountain View, CA. The results of the field studies were published in 1990, five years after the original publication by Wilson and Wilson (Semprini *et al.*, 1990:715). These studies used methane as the primary substrate and oxygen gas as the source of oxygen for aerobic cometabolism of TCE, *cis*-1,2-, and *trans*-1,2-dichloroethylene (*c*-DCE, and *t*-DCE), and vinyl chloride (VC). Results indicated that the methane consuming consortium developed was highly effective at degrading *t*-DCE and VC, but removal of TCE and *c*-DCE was not as successful (Semprini *et al.*, 1990:715).

The low removal efficiency of TCE and *c*-DCE using methane as the primary substrate led to the exploration of other potential primary substrates. The studies were again conducted at the Moffett Federal Airfield and focused on the utility of phenol as a primary substrate, again using oxygen gas as the source of oxygen. The studies, conducted over two field seasons with results published in 1993, found phenol to be superior to methane for *in situ* aerobic cometabolic degradation of TCE and *c*-DCE (Hopkins *et al.*, 1993:2542).

Toluene was also evaluated at the Moffett site for use as a primary substrate for the cometabolic degradation of TCE. Additionally, hydrogen peroxide was evaluated as an oxygen source. The studies concluded that toluene is an effective primary substrate with performance levels very similar to that of phenol. Hydrogen peroxide was also found to

be a good source of oxygen, achieving TCE removals similar to those achieved when using oxygen gas. Finally, the studies verified a laboratory study (Dolan, 1994:303) that the presence of 1,1-DCE as a co-contaminant would significantly reduce TCE removal efficiencies (Hopkins and McCarty, 1995:1628).

A summary of the Moffett Federal Airfield studies is provided in Table C-1 (Hopkins and McCarty, 1995:1635).

Table C-1. Efficiency of Chlorinated Aliphatic Hydrocarbon Removal Obtained at the Moffett Federal Airfield Site with Different Primary Substrates (after Hopkins and McCarty, 1995:1635)

PRIMARY SUBSTRATE	CONC. (mg/L)	% REMOVAL TCE	1,1-DCE	*c*-DCE	*t*-DCE	VC
METHANE	*6.6*	*19*	*NE*[a]	*43*	*90*	*95*
PHENOL	*12.5*	*94*	*54*	*92*	*73*	*>98*
TOLUENE	*9*	*93*	*NE*	*>98*	*75*	*NE*

[a]NE = Not Evaluated

With the lessons learned from the initial field evaluations at the Moffett Federal Air Field, the next logical technology development step was a full-scale technology demonstration. As presented in Chapter 2, full-scale technology demonstrations play an important role in the transfer of an environmental remediation technology. The data gathered during these demonstrations may be used to conclusively prove the ability of a technology to perform and to define the conditions that are most appropriate for technology implementation.

The site selected for the demonstration of *in situ* aerobic cometabolic bioremediation was Site 19 at Edwards AFB. Edwards AFB is located on the western portion of the Mojave Desert, California. Site selection was critical to the full-scale demonstration. Like any environmental technology, *in situ* aerobic cometabolic bioremediation is best suited for use at some sites while inappropriate at others. The results at the Moffett studies were used to select a site that was most appropriate for the full-scale technology demonstration (McCarty *et al.*, 1997).

In addition to the technical criteria used to select a site, the researchers were interested in finding a site that would be overseen by regulators and project management personnel supportive of the evaluation of an innovative technology. This was particularly important in the case of *in situ* aerobic cometabolic bioremediation because the chosen primary substrate for the demonstration, toluene, is a moderately hazardous regulated chemical. Regulators would have to approve the injection of the chemical into the subsurface for the full-scale technology demonstration to become a reality. The Moffett field studies conducted over the previous decade with peer reviewed results were a factor in the acceptance of the demonstration by Edwards AFB remedial project managers and federal, state, and local officials tasked with overseeing the cleanup at Site 19. Additionally, a near real-time monitoring system was proposed for immediate notification of unacceptable toluene concentrations migrating from the site and a contingency plan for toluene removal was prepared should it be needed (McCarty *et al.*, 1997).

The full-scale demonstration provided extensive data which could be used to evaluate *in situ* aerobic cometabolic bioremediation. The demonstration also showed how various strategies could be used to implement the process. For example, methods to alleviate the phenomena known as bioclogging were evaluated. Bioclogging is the preferential growth of microorganisms near the injection well where nutrients are most abundant (Taylor *et al.*, 1993:325). This preferential growth can cause the injection well to become partially clogged with biomass. One solution to this problem is the injection of hydrogen peroxide as an oxygen source. The injected hydrogen peroxide enters the subsurface in the bioclogged zone in concentrations high enough to be toxic to the microorganisms responsible for the bioclogging. As the hydrogen peroxide migrates away from the well it hydrolyzes, providing valuable oxygen to the *in situ* system. Additionally, pulse injection of the primary substrate, thereby limiting microbial growth in the region close to the injection well, may be appropriate. Finally, well-redevelopment is a strategy that has been shown to alleviate not only problems associated with bioclogging but also those associated with the presence of fines which tend to clog pumping and injection wells (McCarty *et al.*, 1997).

The above discussion of bioclogging is offered to illustrate the sort of phenomena that may be elucidated through full-scale demonstrations that may not be adequately evaluated or possibly not even apparent in laboratory or other preliminary studies. The importance of full-scale demonstrations to fully understand the rate limiting processes and practical applications of a particular environmental remediation technology is made clear by this discussion.

The full-scale demonstration at Edwards AFB, Site 19, verified that *in situ* aerobic cometabolic bioremediation is an effective environmental remediation technology. The demonstration yielded TCE removal efficiencies of 95 to 97 percent. Toluene degredation was 99.98 percent, leaving an average of 1.2 to 1.3 μg/L at the boundaries of the treatment zone, well below the maximum goal of 20 μg/L set by regulatory personnel (McCarty *et al.*, 1997). The full-scale demonstration also achieved an important objective of full-scale technology demonstrations by compiling and documenting information that should be relevant to site managers and regulators considering the use of the technology.

Advantages / Disadvantages of *In Situ* Aerobic Cometabolic Bioremediation

Many authors cite the advantages of *in situ* aerobic cometabolic bioremediation over traditional pump-and-treat technology (McCarty *et al.*, 1997, Saaty *et al.*, 1995:290, Taylor *et al.*, 1993:324). These advantages include: the avoidance of costs associated with pumping groundwater to the surface to be treated; the avoidance of an above ground treatment system to treat groundwater contaminants; TCE is destroyed in the process and not simply concentrated in another medium for disposal; disposal of treated groundwater is not an issue; and uncontaminated groundwater is not polluted by bringing it into the contaminated zone as generally occurs in pump-and-treat systems (McCarty *et al.*, 1997). Additionally, Saaty *et al.* indicates that *in situ* bioremediation has been shown to require less time for remediation than pump-and-treat technology (Saaty *et al.*, 1995:292). Taylor *et al.* explains that this is due to the highly heterogeneous nature of most subsurface medium, which creates preferential flowpaths for the extracted groundwater. With pump-

and-treat technology, less permeable subsurface regions receive less remediation and remain as sources of residual contamination to recontaminate the cleaned-up regions (Taylor *et al.*, 1993:324).

One disadvantage of *in situ* bioremediation of chlorinated aliphatics is that it is commonly a cometabolic process requiring a regulated chemical, such as toluene, to be supplied as the primary substrate (McCarty *et al.*, 1997). Regulatory approval for injection of a regulated chemical into the subsurface presents obvious obstacles. Experiences at Site 19 suggest that as long as sufficient oxygen is present and the aquifer has sufficient nutrients to support biological growth, concentrations (of toluene) well below levels of regulatory concern can be achieved (McCarty *et al.*, 1997). Additionally, toluene is also biodegradable anaerobically so that even if sufficient oxygen were not available, toluene would still be degraded to below levels of regulatory concern (McCarty *et al.*, 1997).

An additional disadvantage associated with *in situ* aerobic cometabolic bioremediation are problems associated with bioclogging. The Edwards AFB Site 19 experienced difficulties associated with bioclogging at the injection well. As indicated earlier, the injection of hydrogen peroxide and well-redevelopment was employed to alleviate the problem. However, at a cost of $4.00 per kg ($1.80 per lb), hydrogen peroxide is quite expensive. For example, the primary substrate used at Site 19, toluene, costs only $0.20 per kg ($0.09 per lb). Well-redevelopment was employed three times at Site 19, once due to a sudden head increase and twice as a routine procedure. On average, well-

redevelopment costs about $1000 per redevelopment (Hopkins, 1996). The use of hydrogen peroxide and periodic well-redevelopment may significantly contribute to the cost of a remediation project (McCarty *et al.*, 1997).

CERCLA Criteria and *In Situ* Aerobic Cometabolic Bioremediation

Chapter 2 presented an overview of the nine CERCLA performance criteria used to evaluate environmental remediation technologies by site managers selecting a technology for use at a particular site. Recall the nine criteria, displayed in Table C-2.

Table C-2. CERCLA Technology Performance Criteria

1. Overall protection of human health and the environment
2. Compliance with all other applicable or relevant and appropriate requirements (ARARs)
3. Long-term effectiveness and permanence
4. Reduction of toxicity, mobility, or volume through treatment
5. Short-term effectiveness
6. Implementability
7. Cost
8. State acceptance
9. Community acceptance

The CERCLA performance criteria shall be revisited here with a brief discussion of how well *in situ* aerobic cometabolic bioremediation should satisfy each of the criteria.

Overall Protection of Human Health and the Environment

Chapter 2 defined this critrerion as one of two threshold criteria in the nine performance criteria, meaning that *in situ* aerobic cometabolic bioremediation must fully satisfy this criterion to be considered for implementation at a contaminated site. As a final assessment to determine whether the technology will function in a safe manner that will provide adequate protection to human health and the environment, this criterion is closely related to other criteria, especially long-term effectiveness and permanence, short-term effectiveness, and compliance with ARARs. Because of this relationship, to the degree that *in situ* aerobic cometabolic bioremediation can satisfy these other criteria, it should be able to satisfy this encompassing criterion of overall protection of human health and the environment (Skumanich, 1994:416).

Compliance with ARARs

This threshold criterion is used to determine how well a proposed environmental remediation technology complies with federal, state, and local environmental laws. Although compliance with ARARs is a relatively straightforward process, there are some ARARs that may pose particular issues for the feasibility of technology implementation. For example, *in situ* aerobic cometabolic bioremediation usually requires the injection of a regulated chemical to the subsurface to achieve the highest removal efficiencies. The use of injectants for *in situ* groundwater remediation is a relatively new concept and although it has been allowed in nearly two-thirds of the States, a lengthy process is required to obtain the necessary State permit, an Underground Injection Control permit, for their use (U.S. EPA, 1996b:2). This might affect the feasibility of implementation if

the permitted allowable level is set below the level for proper stimulation of the microbes or if expedient cleanup start-time is critical (Skumanich, 1994:417). As discussed earlier, McCarty *et al.* indicates that experiences at Site 19 suggest that as long as sufficient oxygen is present and the aquifer has sufficient nutrients to support biological growth, concentrations (of toluene) well below levels of regulatory concern can be achieved. Additionally, toluene is also biodegradable anaerobically so that even if sufficient oxygen were not available, regulatory concerns may not pose any substantial problems (McCarty *et al.*, 1997).

With the knowledge gained and documented during the Moffett Federal Airfield studies and the full-scale evaluation at Site 19, parties wishing to implement this technology are equipped with hard data supporting the ability of the technology to comply with ARARs. The degree to which state and local officials charged with overseeing a remediation project accept the data will determine how well *in situ* aerobic cometabolic bioremediation satisfies this criterion.

The next five CERCLA performance criteria are balancing criteria. The performance of *in situ* aerobic cometabolic bioremediation does not have to fully satisfy each of these criteria. Instead, the criteria are used as overall performance indicators, meaning that for *in situ* aerobic cometabolic bioremediation to be selected for implementation at a site, it must demonstrate the best overall performance relative to these criteria when compared to alternative environmental remediation technologies (Skumanich, 1994:416).

Long-Term Effectiveness and Permanence

This criterion will be used to evaluate the ability of *in situ* aerobic cometabolic bioremediation to reliably protect human health and the environment, after the cleanup is completed. Under this criterion EPA has generally favored permanent treatment technologies (destruction) over technologies that pose the possibility of contaminants being re-released to the environment (containment). EPA also favors technologies that treat contaminants at the site rather that those that require removal to off-site locations (Skumanich, 1994:418).

Because *in situ* aerobic cometabolic bioremediation is a permanent treatment process that fully degrades contaminants into innocuous substances, it should be preferred under this criterion. The *in situ* nature of the technology avoids risks associated with transferring contaminants to another site or media and because of the permanence of the process, little will be required in terms of long-term maintenance after cleanup is complete.

Reduction of Toxicity, Mobility, and Volume through Treatment

The objective of this criterion is to measure the degree to which *in situ* aerobic cometabolic bioremediation includes destruction of the contamination, as opposed to containment or disposal elsewhere. Again, because *in situ* aerobic cometabolic bioremediation is a process that leads to complete degradation of a contaminant to harmless substances, it should be favored under this criterion (Skumanich, 1994:419).

Short-Term Effectiveness

Under this criterion, technologies favored are those that require a relatively short and uncomplicated construction period and a relatively short time to implement. Additionally, those technologies that pose the least disruption to the environment are preferred as are those whose impacts to the environment can be easily monitored. *In situ* aerobic cometabolic bioremediation may receive mixed evaluation under this criterion. In favor of the technology, little disruption to the environment is posed (certainly no more than other treatment technologies) and although workers are exposed to moderately hazardous chemicals (toluene and hydrogen peroxide), short-term risks to workers are minimal. If rapid reduction in contaminant is top priority for a particular site, *in situ* aerobic cometabolic bioremediation will likely score poorly under this criterion (Skumanich, 1994:419).

An additional concern under this criterion is the injection of toluene or some other regulated chemical as the primary substrate. Obviously, this technique presents some short-term disruption to the environment. However, as demonstrated at Site 19, this disruption is localized and does not extend beyond the treatment zone.

Implementability

The objective of this criterion is to measure the technical and administrative feasibility of a proposed remedy. Implementation of *in situ* aerobic cometabolic bioremediation is relatively straightforward, requiring little in the way of material or labor. In terms of general availability of goods and materials, the technology should receive favorable

evaluations under this criterion. However, a critical aspect of this criterion is how well the technology has been demonstrated for use, and how reliable the technology will be once it is fully operational. Until *in situ* aerobic cometabolic bioremediation is generally recognized as an accepted technology, regulator acceptance barriers may delay implementation of the technology at particular sites. While it is true that all innovative environmental remediation technologies face regulatory barriers, it is particularly true for *in situ* aerobic cometabolic bioremediation because of the need to introduce hazardous substances to the subsurface. Additionally, monitoring of the *in situ* system presents some short-term implementation challenges as the monitoring system would likely have to be demonstrated before full system operation could begin (Skumanich, 1994:420). Although monitoring an *in situ* process is problematic, the full-scale demonstration at Site 19 demonstrated that monitoring technology is available and able to perform well. The peer reviewed documentation of the Moffett Federal Airfield studies combined with the extensive full-scale technology demonstration at Site 19 and its accompanying peer reviewed literature should prove to be important factors in the overall ability of *in situ* aerobic cometabolic bioremediation to satisfy this criterion.

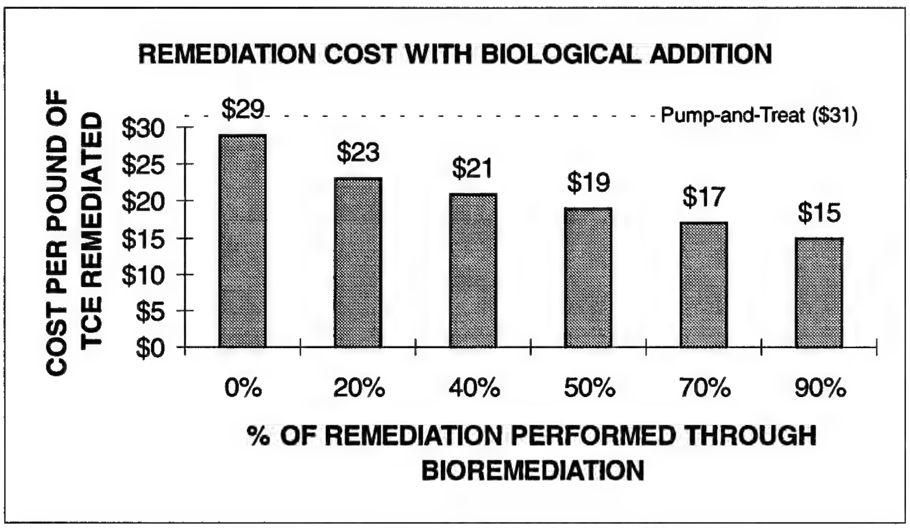
Cost

The objective of this criterion is to identify technologies that have reasonable costs, not necessarily the technology with the lowest cost. One of the strongest arguments for bioremediation technology is that it can present significant cost savings over more conventional treatment technologies (Skumanich, 1994:420). Some discussion shall be presented here exploring the cost of *in situ* aerobic cometabolic bioremediation.

At the Savannah river demonstration site Saaty *et al.* (1995) compared the cost effectiveness of *in situ* bioremediation with traditional pump-and-treat technology to remediate a TCE contaminated plume. In this comparison, Saaty *et al.* compares two dual-remediation systems acting on different sections of the plume. The analysis is conducted in parallel (over the same period of time) so as to avoid obtaining unreliable results as is commonly the case when bioremediation tests are conducted sequentially. The first of these systems evaluated is a pump-and-treat system combined with soil vapor extraction. The second system is composed of *in situ* cometabolic bioremediation using methane as the primary substrate combined with *in situ* air stripping. Therefore, the second system is composed of a physical component, *in situ* air stripping, and a biological component, *in situ* bioremediation. The injection and extraction wells were placed horizontally in this system rather than in the vertical fashion employed at Site 19. Saaty *et al.* reports that the biological component of the *in situ* system proved to be the major factor in determining the cost effectiveness of the *in situ* system (Saaty *et al.*, 1995:292). Based upon this conclusion, Saaty *et al.* normalizes the physical *in situ* air stripping process of the second system to the soil vapor extraction process of the first system, effectively negating the two processes from a cost comparison calculation between the two systems –the two processes essentially cancel each other. This allows a net present value calculation to be performed which directly compares *in situ* bioremediation with pump-and-treat technology. This calculation suggests that *in situ* bioremediation is cost effective when compared with traditional pump-and-treat remediation technology. Saalty *et al.* shows that as the biological component, *in situ* bioremediation, of the dual system increases, the cost per pound of TCE remediated decreases (Saaty *et al.*,

1995:293). Figure C-4 displays cost savings due to the biological portion of the *in situ* system over pump-and-treat (Saaty et al., 1995:293). The figure suggests that when no bioremediation is occurring, *in situ* air stripping is less expensive than traditional pump-and-treat technology ($29 per lb. TCE remediated using *in situ* air stripping versus $31 per lb. TCE remediated using pump-and-treat). As *in situ* bioremediation progressively contributes to the destruction of TCE, the cost saving over pump-and-treat grows. It should be noted that these values are strictly projected values based on the actual costs experienced at the Savannah River site.

Figure C-4. Remediation Cost with Biological Addition at the Savannah River Site



Saaty *et al.* reports that at the Savannah River demonstration where approximately 40% of TCE reduction was assumed to be due to bioremediation and assuming *in situ* air stripping and soil vapor extraction costs were equal, the *in situ* system costs about $21 per pound of TCE remediated. The traditional pump-and-treat/vapor extraction system cost

about $31 per pound of TCE remediated. A ratio of *in situ* bioremediation to pump-and-treat shows that *in situ* bioremediation is 32% less expensive than the traditional technology (Saaty *et al.*, 1995:292).

Based on studies such as the Savannah River site evaluation, *in situ* aerobic comteabolic bioremediation should score well under the cost criterion. Additionally, costs associated with pumping groundwater to the surface are avoided as are hazardous waste disposal fees (McCarty, 1997).

The final two criteria are modifying criteria. As described in Chapter 2, the purpose of modifying criteria is to ensure that state and local issues not directly addressed in the threshold and balancing criteria are given adequate attention.

State Acceptance

This criterion will be used to assess the degree to which *in situ* aerobic cometabolic bioremediation addresses any policy or administrative issues that the state may have. In general, state concerns tend to be with issues similar to those addressed in other areas of the performance criteria. It is likely that the performance of *in situ* aerobic cometabolic bioremediation under this criterion will be a reflection of its reliability, permanence, ease of implementation, cost, and ability to meet ARARs (Skumanich, 1994:421). In the case of the full-scale evaluation of *in situ* aerobic cometabolic bioremediation of TCE at Site 19, use of the technology was strongly supported by State of California regulators.

Community Acceptance

This criterion will be used to measure the acceptance of *in situ* aerobic cometabolic bioremediation by the local community. As in the previous criterion, community concerns tend to be with issues similar to those addressed in other areas of the performance criteria. It is likely that the performance of *in situ* aerobic cometabolic bioremediation under this criterion will be favorable if it performs well in other areas of the performance criteria. Note, however, that community concerns are sometimes "emotional." For example, stimulating microbial growth in the subsurface may lead some community members to be concerned about the ramifications of an increased population of "mutant" microorganisms. Additionally, community members may become concerned over the introduction of toluene as primary substrate –the idea that the introduction of this compound will eventually cause cancer or some other disease in members of the community. DOE, through its VOC-Arid Integrated Demonstration Program has published a report (Peterson and McCabe, 1994) that defines many of the community concerns that are specific to *in situ* bioremediation. These concerns can usually be allayed through community education and communication. Skumanich (1994:421) reports that, overall, the public generally has a favorable opinion of bioremediation technology. In the case of the full-scale evaluation of *in situ* aerobic cometabolic bioremediation of TCE at Site 19, the local community, after being briefed on the site remedial plans, offered no objections to the use of the technology.

Summary of Current Status

The *in situ* aerobic cometabolic bioremediation full-scale demonstration at Edwards AFB was the culmination of over a decade of research and development. The performance of the technology combined with the extensive documentation gathered at Site 19 should be an important factor in overcoming some of the barriers to technology transfer presented in Chapter 2.

Review of the CERCLA performance criteria as they relate to *in situ* cometabolic bioremediation suggests that the technology has the elements necessary to perform well under the criteria. Presumably, one of the largest hurdles to implement the technology is gaining the approval to inject chemicals into the groundwater of site remedial managers and federal, state, and local regulators. However, the full-scale evaluation at Site 19 demonstrated that these concerns need not be an insurmountable barrier to the implementation of *in situ* aerobic cometabolic bioremediation.

The Next Step Toward Full-Scale Implementation

The second goal of this thesis is:

- To present *in situ* aerobic cometabolic bioremediation as an example of an innovative technology currently being evaluated in the field in order to demonstrate strategies and techniques that may be useful in transitioning the technology to full-scale implementation.

By tracing the history of *in situ* aerobic cometabolic bioremediation from its initial conception to the current state of the technology, the first part of this appendix has

accomplished part of the above goal –"to present *in situ* aerobic cometabolic bioremediation as an example of an innovative technology currently being evaluated in the field." The remainder of this appendix will focus on two primary topics. First, some of the most important technology transfer actions already accomplished will be identified. Second, based on the results and conclusions presented in Chapters 5 and 6, technology transfer actions that should be useful in transitioning the technology to full-scale implementation will be identified –the second part of the above goal.

Technology Transfer Accomplishments

While *in situ* aerobic cometabolic bioremediation has not yet been commercialized, some of the most important decisions and technology transfer actions aimed at moving the technology to full-scale implementation have been accomplished. Three of these significant actions are covered below.

Full-Scale Technology Demonstration

The first part of this appendix focused on the history of *in situ* aerobic cometabolic bioremediation from conception to its current status –completion of a full-scale technology demonstration at Edwards Air Force Base. The results of this thesis suggest that technology demonstrations are extremely vital to the transfer of an environmental remediation technology. Without such a demonstration, cost and performance data is likely impossible to generate with any degree of certainty. Without reliable and credible cost and performance data, there is practically no possibility of regulators and consultants giving serious consideration to the technology when selecting cleanup remedies.

Patents

The results and conclusions presented in Chapters 5 and 6 suggest that technology patents on environmental remediation technologies are only appropriate when there exists significant interest, stimulated by financial incentive, by a commercial sector firm in the technology. When this happens, obtaining a patent may be instrumental in convincing a commercial sector firm to pursue a license to implement the technology and dedicate significant effort toward promoting the technology. Such was the case with NoVOCs. However, strong commercial interest did not exist during the developmental stages of *in situ* aerobic cometabolic bioremediation. The developers of the technology, recognizing that a patent may serve to inhibit technology transfer, were wise not to pursue a patent.

Information Dissemination in Peer Reviewed Literature

Results of this thesis have demonstrated the necessity of published research that has been scrutinized by the scientific community. Regulators and consultants, especially, demonstrated the value they place on these publications. The researchers involved with *in situ* aerobic cometabolic bioremediation have been committed to publishing their findings in respected peer reviewed journals and conference proceedings. Table C-3 lists a sampling of the peer reviewed publications addressing *in situ* aerobic cometabolic bioremediation.

Table C-3. Peer Reviewed Publications on *In Situ* Aerobic Cometabolic Bioremediation

Publication	Description
• Hopkins, G.D. and P.L. McCarty. "Field evaluation of in situ aerobic cometabolism of trichloroethylene and three dichloroethylene isomers using phenol and toluene as the primary substrates," Environmental Science & Technology, Vol.29, No.6: 1628-1637 (1995)	• describes the use of phenol and toluene with oxygen gas and hydrogen peroxide at Moffett (in preparation for Edwards) as well as summarizing the results of prior Moffett work with methane. Also shows the problems in the field caused by the presence of 1,1-DCE as a co-contaminant with TCE
• Dolan, M. and P.L. McCarty. "Methanotrophic chloroethene transformation capacities and 1,1-dichloroethylene transformation product toxicity," Environmental Science & Technology, Vol.29, No.11: 2741-2747 (1995)	• a lab study showing how the presence of 1,1-DCE as a co-contaminant may severely inhibit TCE cometabolism
• Semprini, L. and McCarty, P. L. "Comparison between model simulations and field results for in situ biorestoration of chlorinated aliphatics: Part 2. Cometabolic transformations," Ground Water, Vol. 30, No.1: 37-44 (1992) • Lang, M.M., P.V. Roberts, and L. Semprini. "Model Simulations in Support of Field-Scale Design and Operation of Bioremediation Based on Cometabolic Degradation," Ground Water, Vol.35 No.4: 565-573 (1997)	• these 3 papers use essentially the same model to describe cometabolic bioremediation. The first paper applies a 1-D model at Moffett, the second paper two-dimensionalizes the 1-D model.
• Jenal-Wanner,U. and P.L. McCarty. "Development and evaluation of semi-continuous slurry microcosms to simulate in situ biodegradation of trichloroethylene in contaminated aquifers," Environmental Science & Technology, 1997.	• describes the lab work that was done to see if bacteria at Edwards would degrade TCE in the presence of toluene and phenol
• McCarty, P.L., M.N. Goltz, G.D. Hopkins, M.E. Dolan, J.P. Allan, B.T. Kawakami and T.J. Carrothers. "Full-scale evaluation of in situ cometabolic degradation of trichloroethylene in groundwater through toluene injection," accepted Environmental Science & Technology, 1997.	• describes entire Edwards AFB demonstration from preliminary modeling to results

Now that the demonstration is complete and reliable data has been gathered, the next step in the technology transfer process is to disseminate information learned from the demonstration. As shown in Chapters 5 and 6, disseminating cost and performance data in a form that is useful to site owners, regulators, and consultants is an important aspect of transferring an environmental remediation technology. The remainder of this appendix will focus on a method of presenting usable cost and performance data for *in situ* aerobic cometabolic bioremediation. Other technology transfer actions that may be appropriate in

transferring *in situ* aerobic cometabolic bioremediation to commercial use will also be suggested.

Recommended Technology Transfer Actions

Cost and Performance Reporting Through Interactive Software

The results of this thesis presented important considerations for the reporting of cost and performance data. These considerations include:

- *"Costs of remediation technologies should be reported as cost per unit volume of the contaminated matrix treated, removed, or contained and as cost per unit mass of each specific contaminant removed, treated, or contained."*
- *"Cost estimates should include one-time start-up costs as well as the up-and-running cost of using the technology."*
- *Cost and performance data should be reported relative to a series of template sites to make comparison of alternative technologies easier.*
- *Developers should clearly identify interest rate and project life assumptions made for cost calculations.*

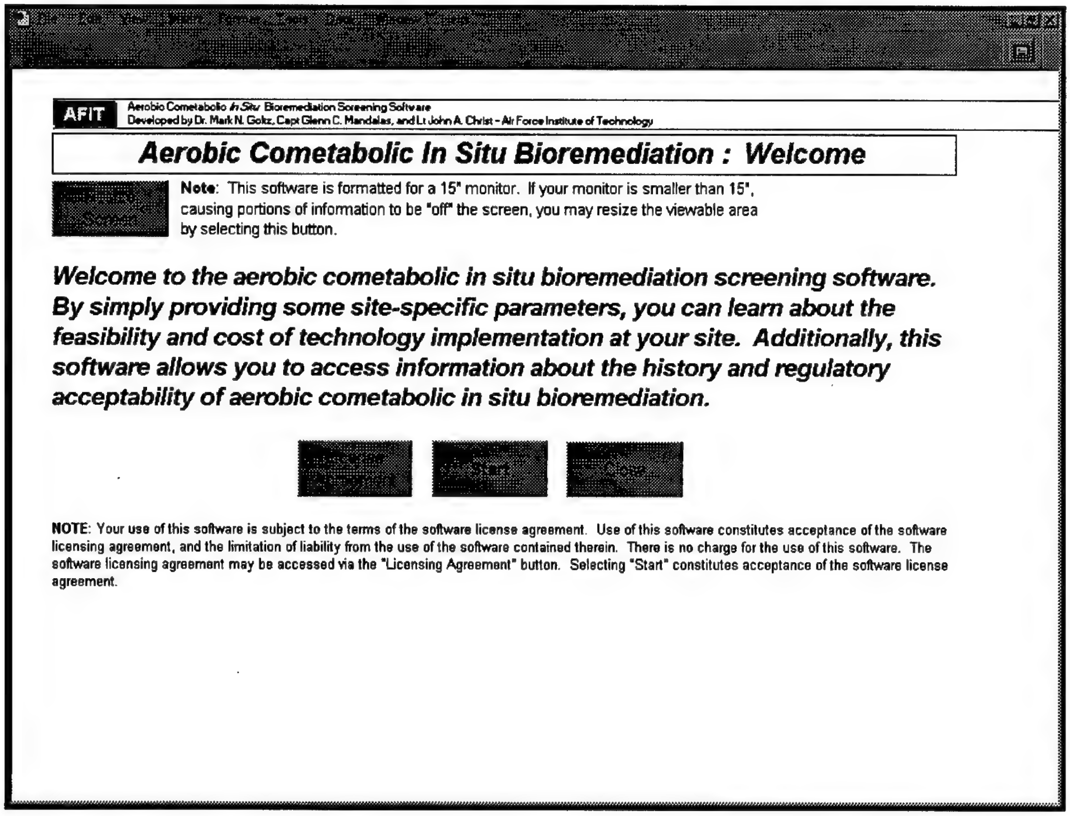
In conjunction with this thesis, computer software based on the full-scale demonstration of *in situ* aerobic cometabolic bioremediation has been developed that demonstrates one method of accomplishing the "best practices" listed above. The software was developed to accomplish three objectives. First, it provides a technology screening tool for technology users and consultants to use to determine whether the technology is appropriate at their site. Second, it gives technology users and consultants the ability to compare *in situ* aerobic cometabolic bioremediation against other technologies in a simple way. Finally, the software publicizes the technology, gaining the interest of technology users and consultants. Although not explicitly identified in the results of this

thesis, technology users (77%) indicate that they are oftentimes overwhelmed by the printed information on innovative environmental remediation technologies that crosses their desks. In many cases, the information is discarded as "junk mail" –never getting read. Technology users indicated that for an innovative technology to get noticed, it is helpful to present it in a way that sets it apart from the other technologies. One way of accomplishing this is through interactive software that can teach the user a lot about a particular technology in a short time. Interviewees indicated that such an interactive product would usually interest them enough that they would explore the software.

About the Software: The software (a copy is located in the disk pouch on the back cover of this thesis) is written in Visual Basic and uses Microsoft Excel 7.0 as the operating platform. Microsoft Excel was selected because it is a powerful spreadsheet program that offered the computing abilities required of the cost calculations. Additionally, Excel should be a familiar operating platform for most technology users, consultants, and regulators. Visual Basic is a computer language that offers the tools needed to construct a program that is user friendly. Additionally, the language allows the programmer to provide options that are familiar to the user such as point-and-click operation, drop-down menus, and scroll bars. For a complete explanation of how to program in Visual Basic using Microsoft Excel as the program driver, the reader should consult the Microsoft Excel Visual Basic User's Guide (Microsoft Corporation, 1994).

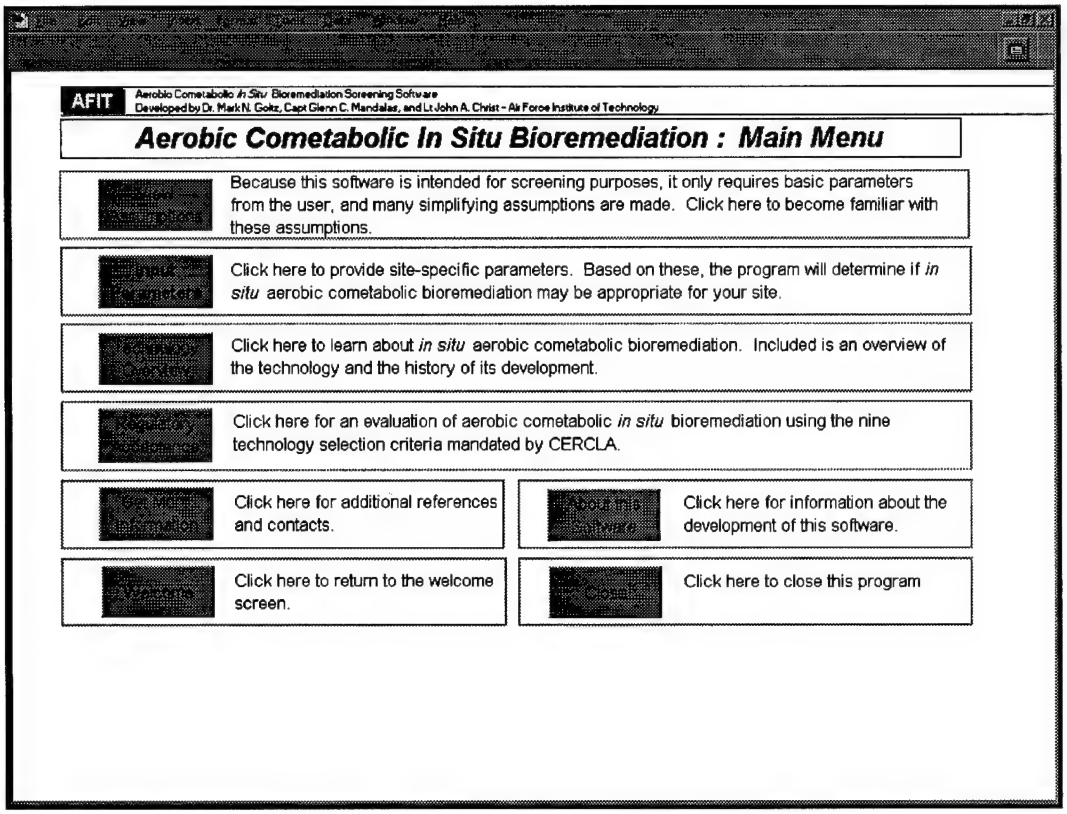
Software Operation: The user is greeted by a welcome page when the software is opened. This page is shown in Figure C-5.

Figure C-5. *In Situ* Aerobic Cometabolic Bioremediation Screening Software: Welcome Page



From the welcome page, the user may elect to view the license agreement, start the program, or close the program. The license simply states that the software is intended to be used as a screening program to determine if *in situ* aerobic cometabolic bioremediation may be appropriate for use at a particular site and that the program should not be used for detailed design. If "Close" is selected, the user is exited from the screening software (but remains in Microsoft Excel). When the user selects "Start," a page is displayed that gives a brief overview of *in situ* aerobic cometabolic bioremediation and displays the conceptual depiction of the technology presented in Figure C-1. After viewing the brief overview, the user may access the main menu, shown in Figure C-6.

Figure C-6. *In Situ* Aerobic Cometabolic Bioremediation Screening Software: Main Menu



From the main menu, the user has nine different options:

- **View Assumptions** - Because the software is meant as a screening tool, a number of simplifying assumptions were made (thus requiring less user input). This button displays the assumptions made.

- **Input Parameters** - This button allows the user to input site specific parameters to determine if *in situ* aerobic cometabolic bioremediation may be appropriate at their site.

- **Technology Overview** - Displays a detailed overview of the technology including the history and current status of the technology. Users may also access figures depicting different methods of technology application depending on site specific geologic conditions (see Figures 7-2 and 7-3).

- **Regulatory Acceptance** - By selecting this option, the user can view the ability of *in situ* aerobic cometabolic bioremediation to satisfy the CERCLA technology selection criteria. Should the user be unfamiliar with the

CERCLA criteria, an overview of the criteria is also available by selecting this option.

- **Get More Information** - If, after using the software, the user is interested in finding out more about the technology, a comprehensive list of references that address *in situ* aerobic cometabolic bioremediation is provided. Additionally, a point of contact, Armstrong Lab Environics Directorate, is identified.

- **About This Software** - Selecting "About This Software" provides the user with information about the development of the screening software, including when it was done, where it was done, and by whom it was done (and how to contact the developers).

- **Welcome** - This button takes the user back to the original welcome screen (Figure C-5).

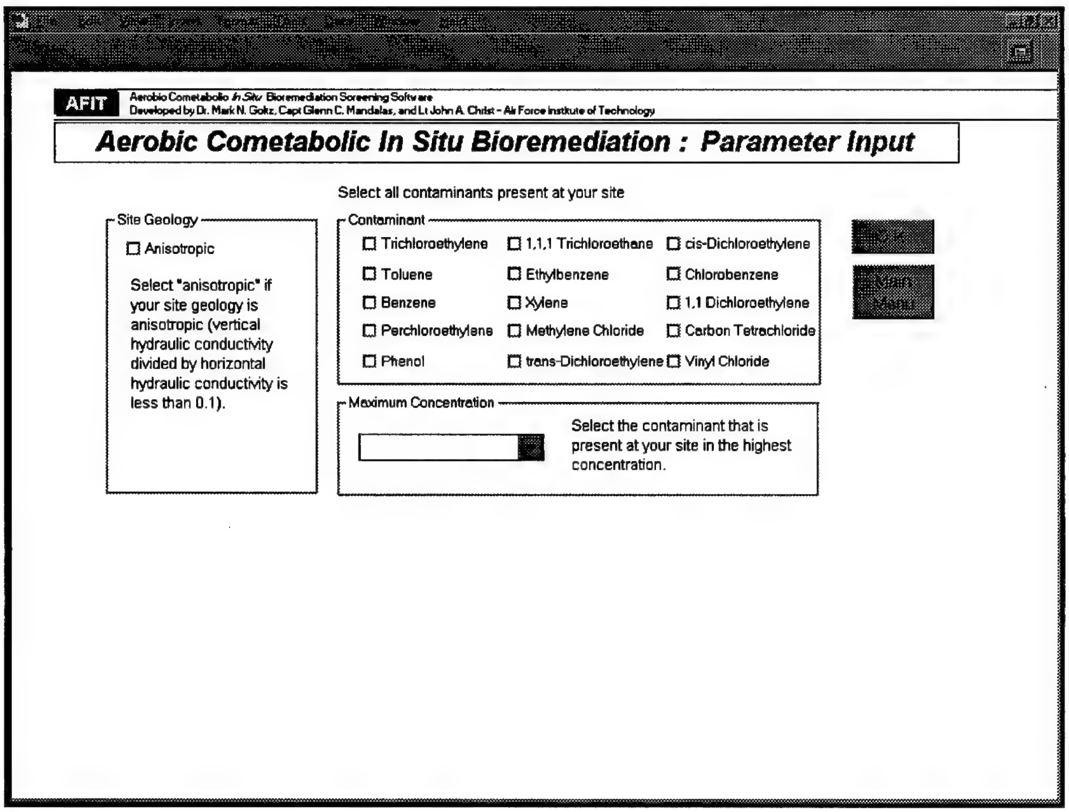
- **Close** - Allows the user to close the screening software and remain in Microsoft Excel. After selecting this button the user is asked whether or not they want to save their changes. Selecting "Yes" allows the user to save any site-specific information that has been identified. Selecting "No" will leave the settings at the last saved configuration.

Selecting "Input Parameters" from the main menu accomplishes the primary goal of the software –evaluating whether the technology may be appropriate for use at a particular site. Therefore, this option will be covered in detail.

After selecting "Input Parameters," the user is provided with the opportunity to indicate whether the site geology is anisotropic or not at their site, and to specify the contaminants present at their site. After selecting all the contaminants present at a site, the user identifies the one present in the highest concentration –the one that the cost calculation will be based upon. Because contaminated groundwater need not be pumped to the surface if site conditions are anisotropic (see Figure C-2), sites having anisotropic geologic conditions may have cleanup costs significantly lower than what the software,

which conservatively assumes isotropic conditions, reports. Users who indicate that their site is anisotropic are alerted to the fact that their actual cost may be significantly lower than that reported by the software. Figure 7-7 displays the first of two parameter input screens.

Figure 7-7. *In Situ* Aerobic Cometabolic Bioremediation Screening Software: Parameter Input Screen #1



In addition to allowing input of isotropy and contaminants present, this screen, in conjunction with the code, acts as an important prescreening tool. For instance, since *in situ* aerobic cometabolic bioremediation is inappropriate for use when 1,1-dichloroethylene is present at a site, if a user selects 1,1-dichloroethylene, a message will appear stating that the technology is inappropriate for the user's particular site. This

phase of the software will also check contaminant combinations for technology appropriateness. For example, although the technology will work on BTEX compounds (benzene, toluene, ethylbenzene, and xylene) since BTEX compounds will aerobically degrade, other technologies are much more appropriate for these compounds as injection of a primary substrate is extraneous. If the user selects one of these contaminants as the sole contaminant present at a site, a message will appear suggesting that while *in situ* aerobic cometabolic bioremediation will work for the site, other technologies are more appropriate. However, if the user selects a BTEX compound in conjunction with an appropriate CAH, such as trichloroethylene, no message appears.

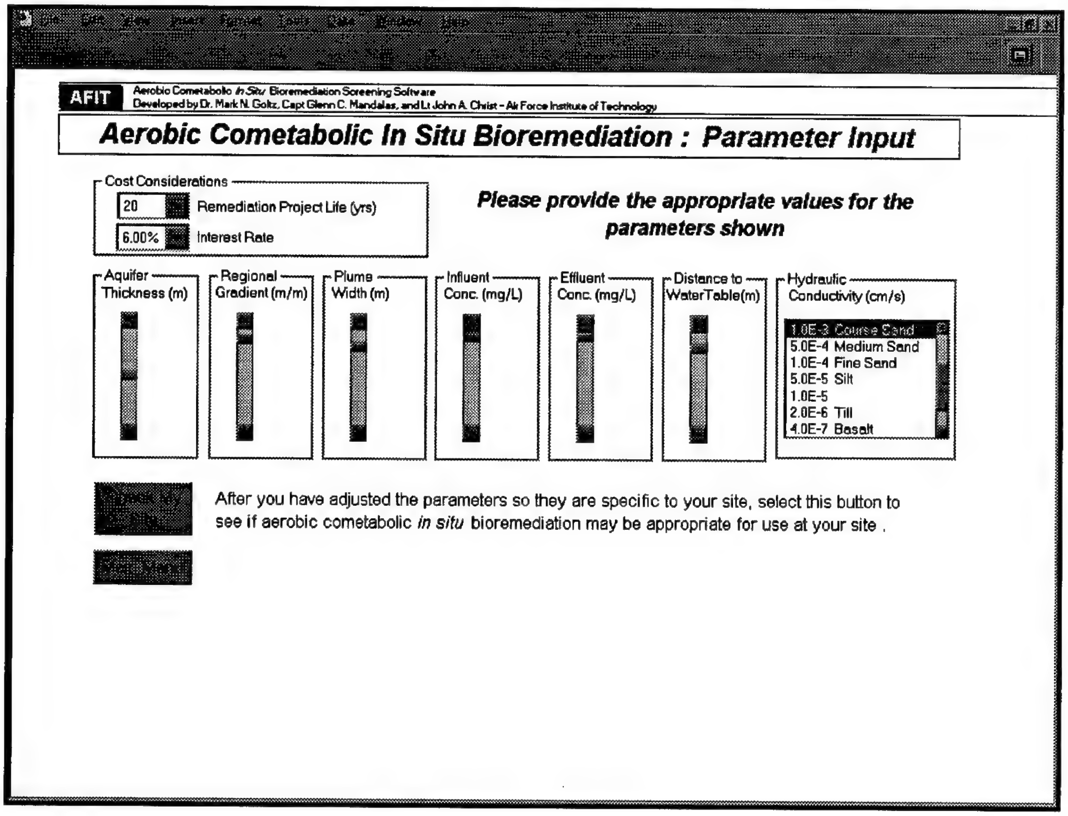
After selecting the appropriate options and selecting "O.K.", a second parameter input screen is displayed, Figure C-8. This screen allows the user to input site specific parameters including aquifer thickness, regional gradient, plume width, influent concentration, desired effluent concentration, distance to water table, and hydraulic conductivity. Additionally, this screen allows the user to specify the interest rate and project life for the software to use in cost calculations.

At the beginning of this section, four recommendations of this thesis that address cost reporting were presented. The second parameter input screen satisfies two of these recommendations. These are:

- *Developers should clearly identify interest rate and project life assumptions made for cost calculations.*

- *Cost and performance data should be reported relative to a series of template sites to make comparison of alternative technologies easier.*

Figure C-8. *In Situ* Aerobic Cometabolic Bioremediation Screening Software: Parameter Input Screen #2



By allowing the user to select the interest rate and project life desired, the first recommendation above is clearly satisfied. Recall the template sites suggested by the NRC (1997:) shown in Table C-4.

Table C-4. Example Template Sites (NRC, 1997:236)

Template Number	Depth to Water Table (m)	Aquifer Thickness (m)	Hydraulic Conductivity	Groundwater Flow Rate (m/year)
1	*4.6 (15 ft)*	*7.6 (25 ft)*	*5.0×10^{-4} cm/sec*	*3 (10 ft/yr)*
2	*4.6 (15 ft)*	*7.6 (25 ft)*	*2.5×10^{-2} cm/sec*	*150 (500 ft/yr)*
3	*4.6 (15 ft)*	*21 (70 ft)*	*5.0×10^{-4} cm/sec*	*3 (10 ft/yr)*
4	*4.6 (15 ft)*	*21 (70 ft)*	*2.5×10^{-2} cm/sec*	*150 (500 ft/yr)*
5	*30 (100 ft)*	*7.6 (25 ft)*	*5.0×10^{-4} cm/sec*	*3 (10 ft/yr)*
6	*30 (100 ft)*	*7.6 (25 ft)*	*2.5×10^{-2} cm/sec*	*150 (500 ft/yr)*
7	*30 (100 ft)*	*21 (70 ft)*	*5.0×10^{-4} cm/sec*	*3 (10 ft/yr)*
8	*30 (100 ft)*	*21 (70 ft)*	*2.5×10^{-2} cm/sec*	*150 (500 ft/yr)*

Note: Soil porosity is assumed to be 25 percent, and hydraulic gradient is assumed to be 0.005 cm/cm for all eight cases.

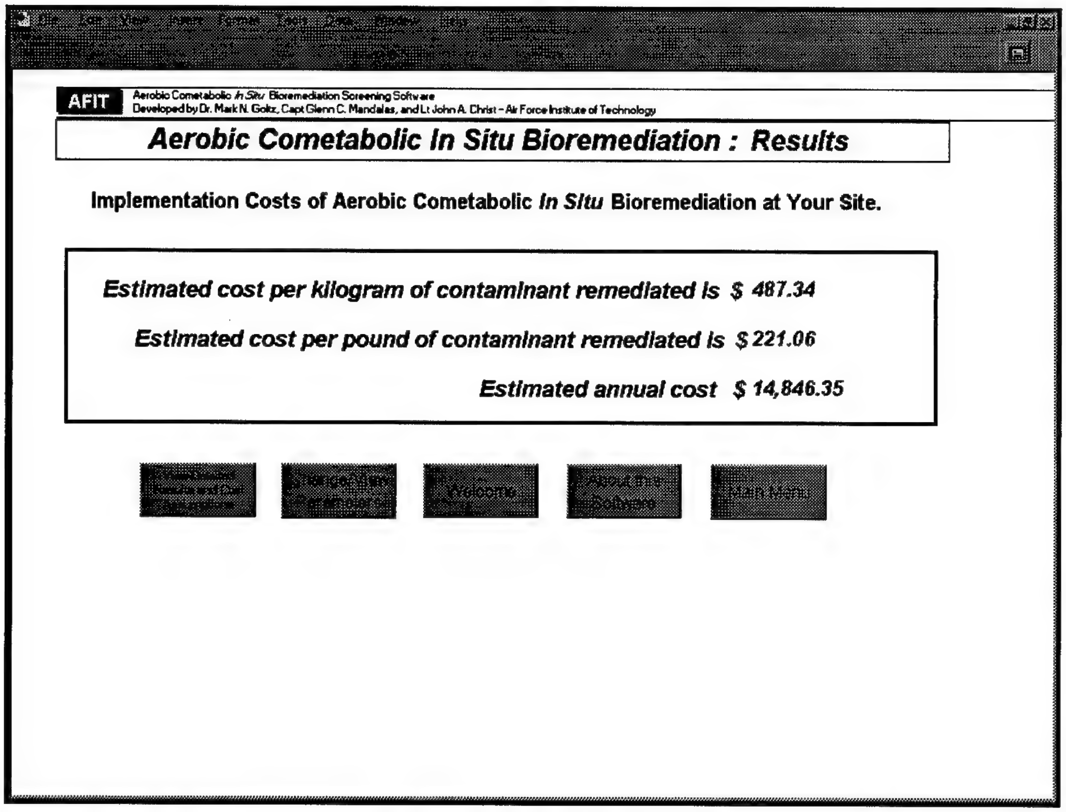
By adjusting parameters on the second input page, users are capable of generating costs for *in situ* aerobic cometabolic bioremediation relative to each of the NRC example template sites. In addition to accommodating the template sites, the screening software is also capable of accommodating almost any variety of site conditions by adjusting the parameters on the second input page. So, while the template sites are a good idea for reporting cost and performance data, interactive screening software can offer even more information and flexibility to site owners. By giving the site owner the flexibility to vary site-specific parameters, the *in situ* aerobic cometabolic bioremediation screening software assures that no matter what template sites are used, the technology can be evaluated against them.

After selecting an interest rate and project life and adjusting the scroll bars to the appropriate site specific values, the user can check the cost of technology implementation. The cost information is displayed to the user as shown in Figure C-9. Recall that the two remaining cost recommendations presented at the beginning of this section are:

- *"Costs of remediation technologies should be reported as cost per unit volume of the contaminated matrix treated, removed, or contained and as cost per unit mass of each specific contaminant removed, treated, or contained."*

- *"Cost estimates should include one-time start-up costs as well as the up-and-running cost of using the technology."*

Figure C-9. *In Situ* Aerobic Cometabolic Bioremediation Screening Software: Technology Cost



This screen presents the cost per mass of contaminant treated. Additional cost information that satisfies the other cost reporting recommendation (i.e. cost per volume of contaminated matrix treated and up-and-running costs) is shown when the user selects the option to view more detailed cost data. When selecting this option, the user sees a pie chart depicting the cost attributable to each cost component (pumping cost, capital cost,

donor cost, acceptor cost), an explanation of the oxygen source (air, molecular oxygen, or hydrogen peroxide depending on user specified conditions), technology costs using other oxygen sources, the number of treatment wells required, cost assumptions, up-and-running costs, and cost per volume of contaminated matrix treated. This scrolling screen is depicted in Figure C-10.

The detailed data provided to the user is significant because it displays the cost in all of the ways suggested in the results section of this thesis. Tables 7 and 8 of the software (shown in Figure C-10) display "up-and-running" cost both as an annual cost and on a cost per mass basis. Table 9 of the software (shown in Figure C-10) displays cost per volume of contaminated water treated. Theses tables satisfy the remaining recommendations for reporting cost data.

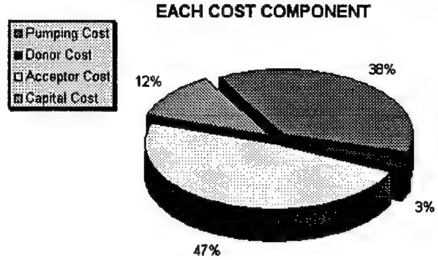
In addition to satisfying all of the cost reporting recommendations, the software displays costs for all possible oxygen sources. As described earlier in this appendix, oxygen is the electron acceptor needed to stimulate microbial growth. There are three sources of dissolved oxygen that may be used: (1) air; (2) molecular oxygen; (3) hydrogen peroxide. Displaying costs as a function of oxygen source is relevant because it provides the user with cost alternatives. For instance, as discussed earlier, hydrogen peroxide may be needed to alleviate bioclogging, even though hydrogen peroxide costs are significantly greater than the costs of molecular oxygen.

Figure C-10. *In Situ* Aerobic Cometabolic Bioremediation Screening Software: Detailed Cost Information

AFIT Aerobic Cometabolic *In Situ* Bioremediation Screening Software
Developed by Dr. Mark N. Goltz, Capt Glenn C. Mandalas, and Lt John A. Christ - Air Force Institute of Technology

Aerobic Cometabolic In Situ Bioremediation : Details

PERCENTAGE OF COST ATTRIBUTABLE TO EACH COST COMPONENT



How your cost was calculated

In order to calculate the cost at your site, the use of three different oxygen sources was considered. The oxygen sources considered were air, molecular oxygen, and hydrogen peroxide. The pie graph shown to the left represents the cost component breakout of the least expensive of the three alternatives. The alternative selected for your site along with the relevant cost components is displayed in Table 1.

Note: **Capital cost** refers to the installation of the system. **Acceptor cost** is the cost of the selected oxygen source (air, oxygen, or hydrogen peroxide). **Donor cost** is the cost of microbial "food" / primary substrate (toluene), and **pumping cost** is the energy cost associated with required pumping to the surface (note that for an anisotropic aquifer, pumping to the surface may not be required, and this cost may be considerably reduced).

YOUR SELECTED OXYGEN SOURCE: MOLECULAR OXYGEN

Table 1. Cost Components of Selected Alternative

	Pumping	Donor	Acceptor	Capital
Annual Cost ($)	5627.52	387.92	7087.23	1743.69

Number of wells required for this system: 2

Well flowrate (cubic meters/day): 619.96

Water table drawdown due to pumping (m): 15.00

Assumptions: Some assumptions were employed to arrive at your cost. These assumptions are listed below

1. Each well has an assumed capital cost of $10,000 for purchase and installation. In addition, an annual cost of $1000 per well for well redevelopment is accounted for in pumping costs.

2. Assumed cost of electron acceptor (based on supplier cost quotes in Ohio):
-Air (blower), $2.77 per kg. of air
-Molecular Oxygen (pressurized tank), $1.74 per kg.of molecular oxygen
-Hydrogen Peroxide, $3.90 per kg. of hydrogen peroxide

3. Assumed dissolved oxygen concentration:
-Air, 3.6 mg/L
-Molecular Oxygen, 18 mg/L
-Hydrogen Peroxide, 30 mg/L

4. Assumed oxygen source delivery methods
-Air, Blowers (assumed purchase of 2 blowers)
-Molecular Oxygen, Pressurized Cylinder
-Hydrogen Peroxide, 50%

(Continued)

Figure C-10. *In Situ* Aerobic Cometabolic Bioremediation Screening Software: Detailed Cost Information (Cont.)

5. Energy costs associated with blower operation are assumed negligible.

6. Sampling costs are assumed negligible.

7. Tax benefits are not considered.

An additional relationship needed for the cost calculation...
Grams of oxygen required per gram of toluene (electron donor): 2.1

Other Alternatives: As described above, there are three oxygen sources that may be used. The results presented thus far are based on the least expensive of the three alternatives. Shown in tables 2 and 3 are the results of the alternative oxygen sources as well as the selected least expensive alternative. Tables 4, 5, and 6 display donor/acceptor concentrations and number of wells required for each oxygen source.

COST AS A FUNCTION OF OXYGEN SOURCE

Table 2. Total Operating Costs ($/yr)

	$/yr
Air	299744.96
O2	14846.35
H2O2	64277.71

Table 3. $/kg or $/lb Contaminant Removed

	$/kg	$/lb
Air	9839.39	4463.12
O2	487.34	221.06
H2O2	2109.97	957.08

DONOR/ACCEPTOR CONCENTRATION AS A FUNCTION OF OXYGEN SOURCE

Table 4. Electron Donor (toluene) Conc.

	mg/L
Air	1.71
O2	8.57
H2O2	14.29

Table 5. Oxygen Source Requirement

	ml/L of Water
Air	0.025
O2	0.023
H2O2	0.077

WELLS REQUIRED AS A FUNCTION OF OXYGEN SOURCE

Table 6. Number of Wells Required

Air	32
O2	2
H2O2	2

OTHER COST EXPRESSIONS

Table 7. Up-and-Running Cost ($/yr)

	$/yr
Air	271802.31
O2	13102.66
H2O2	62534.02

Table 8. Up-and-Running Contaminant Removed

	$/kg	$/lb
Air	8922.15	4047.06
O2	430.11	195.09
H2O2	2052.73	931.11

Note: Tables 7 and 8 are "Up-and-running" costs, meaning that no capital costs are incorporated in them.

Table 9. Cost per Volume of Contaminated Matrix Treated

	$/cubic meter of water treated
Air	18.20
O2	0.90
H2O2	3.90

Now that we know the recommended methods of reporting cost data, and the software has been shown to use the methods, we shall analyze the costs of *in situ* aerobic cometabolic bioremediation using the template sites suggested by the NRC (1997:236).

Table C-5. *In Situ* Aerobic Cometabolic Bioremediation Costs Relative to the NRC Template Sites

Template Number	Depth to Water Table (m)	Aquifer Thickness (m)	Hydraulic Conductivity	Groundwater Flow Rate (m/year)
1	4.6 (15 ft)	7.6 (25 ft)	5.0×10^{-4} cm/sec	3 (10 ft/yr)
2	4.6 (15 ft)	7.6 (25 ft)	2.5×10^{-2} cm/sec	150 (500 ft/yr)
3	4.6 (15 ft)	21 (70 ft)	5.0×10^{-4} cm/sec	3 (10 ft/yr)
4	4.6 (15 ft)	21 (70 ft)	2.5×10^{-2} cm/sec	150 (500 ft/yr)
5	30 (100 ft)	7.6 (25 ft)	5.0×10^{-4} cm/sec	3 (10 ft/yr)
6	30 (100 ft)	7.6 (25 ft)	2.5×10^{-2} cm/sec	150 (500 ft/yr)
7	30 (100 ft)	21 (70 ft)	5.0×10^{-4} cm/sec	3 (10 ft/yr)
8	30 (100 ft)	21 (70 ft)	2.5×10^{-2} cm/sec	150 (500 ft/yr)

Note: Soil porosity is assumed to be 25 percent, and hydraulic gradient is assumed to be 0.005 cm/cm for all eight cases.
Source: (NRC, 1997:236)

Template Number	Annual Cost ($)	$/Kg Remediated	Up-and-Running Annual Cost ($)	Up-and-Running $/Kg Remediated	$/m^3 of Water Treated
1	4,856.98	5,159.59	3,113.28	3,307.26	5.16
2	58,618.22	622.70	51,643.56	548.61	0.62
3	4,683.36	1,895.30	2,939.67	1,189.65	1.90
4	138,898.12	562.10	135,410.73	547.99	0.56
5	4,972.79	5,282.62	3,229.10	3,430.29	5.28
6	84,355.41	896.11	82,611.72	877.59	0.90
7	5,337.54	2,160.03	3,593.85	1,454.38	2.16
8	230,383.86	932.33	226,896.47	918.22	0.93

Note: Interest rate is assumed to be 6%. Project life is assumed to be 20 years. Costs reported are based on a 150 m wide TCE plume with an influent concentration of 1000 ppb and an effluent concentration of 5 ppb.

A number of assumptions are made to arrive at the costs reported in Table C-5. These cost-related assumptions as well as other assumptions that are built into the software are presented in Table C-6.

Table C-6. *In Situ* Aerobic Cometabolic Bioremediation Screening Software Assumptions and Standards

CAPITAL COSTS	
Well Installation ($/well)	10,000[a]
Blower Cost (when air is selected oxygen source) ($/unit)	250
Number of Blowers Purchased (when air is selected)	2
OPERATING COSTS	
Well Redevelopment ($/well-yr)	1,000[b]
Electricity ($/Kw-hr)	0.196[b]
Wire-to-Water Efficiency (%)	63
Primary Substrate (toluene) ($/kg)	0.2[c]
Electron Acceptor Air/O_2/H_2O_2 ($/Kg)	2.77[d]/1.74[e]/4.0[b]
Energy costs for blower operation (air)	Negligible
Sampling Costs	Negligible
OTHER ASSUMPTIONS or STANDARDS	
Maximum Allowable Aquifer Drawdown (%)	30
Oxygen Delivery Method Air/O_2	Blower/Pressurized Cylinder
Dissolved Oxygen Concentration Air/O_2/H_2O_2 (mg/L)	3.6/18/30
mg of Dissolved Oxygen Required / mg of Donor	2.1
Primary Substrate Concentration Air/O_2/H_2O_2 (mg/L)	1.7 / 8.6 / 14.3
Organism Decay Rate (1/d)	0.15
Yield Coefficient (mg/mg)	0.77
Utilization Rate	
• trichloroethylene (TCE)	0.07[f]
• trans-dichloroethylene (trans-DCE)	0.25[g]
• cis-dichloroethyelen (cis-DCE)	0.035[g]
• vinyl chloride (VC)	0.25[g]

a. Personal Communication with Dr. Mark Goltz
b. Hopkins, 1996
c. McCarty *et al.*, 1997
d. Poolproducts Inc., 1997 cost data
e. Based on Ohio distributor cost
f. Jenal-Warner and McCarty, 1997
g. Semprini and McCarty, 1992

The validity of the methodology employed by the software (discussed later in this appendix) is verified by the cost results reported in Table C-5 which appear, at least qualitatively, to make sense. For instance, because *in situ* aerobic cometabolic bioremediation uses an injection and extraction well system, one would expect a high hydraulic conductivity, shallow water table, and thick aquifer to be ideal conditions for the technology. Template site #4 describes these conditions –and is the template that represents the lowest cost per mass remediated ($562.10/Kg). Note, however, that this

template produces the highest annual cost ($138,898.12/yr). This also is expected. Because the geologic conditions are such that groundwater can flow relatively easily, this system can treat a relatively high volume of water annually. In contrast, consider template site #5. Template #5, which is the opposite of template #4, returns costs that are relatively low annually ($4,972.79/yr), but quite high on a mass basis ($5,282.62/Kg). While the technology may be effective at a template #5 site, geologic conditions are working against the technology. For example, the low groundwater flow rate of template #5 causes little groundwater to enter the extraction well on an annual basis, therefore pumping costs at the template #5 site are minimal, about 10% of the pumping costs for the #4 site. However, because only a small volume of water is treated annually, the cost per mass of contaminant remediated is significant, about ten times the #4 site. Thus, it is apparent that cost per mass of cost per volume of water treated are appropriate parameters to use to evaluate technology costs at a site

In a discussion presented earlier in this appendix, Saaty (1995:293) reported a bioremediation cost of under $30 per pound of TCE remediated at the Savannah River site. Because the software takes a conservative approach, costs this low will rarely be reported. In fact, for geology conditions similar to those at the Savannah River site, the software returns remediation costs on the order of $100 per pound of TCE remediated. There are two reasons for this. First, the software takes a conservative approach. For instance, site geology is assumed to be isotropic. So, while a site may be anisotropic, not requiring water to be pumped to the surface, pumping costs are still included. Also, when greater interflow between wells is required, the program decreases the distance between

wells and adds more. In reality, a second row of fewer wells could be added. The second reason that costs are somewhat higher than those reported by Saaty is due to economies of scale. As contaminant concentration increases, cost per mass of contaminant remediated decreases. The Savannah River site demonstration was conducted on a plume contaminated with 25 ppm TCE. Bioremediation, which is typically inappropriate as the sole technology at concentrations this high, was appropriate at the Savannah River site because it was employed in conjunction with pump-and-treat. Since the screening program assumes that *in situ* aerobic cometabolic bioremediation is the only technology being used on a contaminated plume or area of plume, influent concentrations above 10 ppm are not permitted. So, although the geologic conditions of the Savannah River site may be used, the contaminant concentration may not. The cost on the order of $100 per pound of TCE remediated, reported at the beginning of this paragraph, is based on a plume contaminated with 10 ppm TCE, not 25 ppm TCE.

The calculations used to derive the cost data in the screening software are based on simplifying assumptions that would be inappropriate for a detailed design of an *in situ* aerobic cometabolic bioremediation system. A basic overview of the methodology employed by the software to calculate costs follows.

Software Cost Calculations: After a user inputs site specific parameters, the program calculates a maximum well flow rate based on allowable drawdown at the treatment well. After determining the maximum well flow rate, system efficiencies are calculated. Both overall removal efficiency (determined by the contaminant

concentration in the plume and regulatory standards) and "single-pass" treatment efficiencies are determined. "Single-pass" treatment efficiency refers to refers to the extent of contaminant treatment during a single-pass through the bioactive zone (see Figure C-3). A simplified process is used to calculate the single-pass treatment efficiency. Instead of allowing the primary substrate and electron acceptor concentrations to vary, a dissolved oxygen concentration is specified for each oxygen source (shown in Table C-6). From these three dissolved oxygen concentrations, the primary substrate (toluene) concentration can be calculated since, based on stoichiometry and cell growth, it is known that 2.1 mg of dissolved oxygen are required/mg of toluene. Therefore, the primary substrate concentrations are found to be 1.7 mg/L when air is used as the oxygen source, 8.6 mg/L when oxygen gas is used, and 14.3 mg/L when hydrogen peroxide is used (Table C-6). Knowing the primary substrate concentrations and assuming other microbiological parameters, the single-pass treatment efficiencies (for each oxygen source) can be calculated. Now that both the overall efficiency and the single-pass treatment efficiency are known, average interflow between wells can be determined since the way to increase the single-pass treatment efficient to meet overall efficiency goals is by recycling the water more than once through the bioactive zone. Knowing the average interflow the software determines how much water in each extraction well is coming from upgradient, thus determining how many wells are required to ensure the entire plume width can be captured. Based on the number of wells, flow in the wells, and assumed costs (Table C-6), total costs are calculated.

For a complete discussion of the mathematics used in the software, interested readers should see Christ (1997). As stated earlier, a number of simplifying assumptions were made. Theses assumptions allow the user to run the software knowing only a few basic site-specific parameters, that are relatively easy to obtain. Again, note that the purpose of this software is not to provide the user with a detailed cost breakdown and remediation system design, but rather to stimulate the site owner's interest in the technology and to provide a quick way of determining the appropriateness of implementing the technology at a specific site.

Performance Reporting: In addition to the cost reporting recommendations, the results of this thesis suggest that developers should also seek to answer two questions when reporting performance data:

1) *"Does the technology reduce risks posed by the soil or groundwater contamination?"*

2) *"How does the technology work in reducing those risks? That is, what is the evidence proving that the technology was the cause of the observed risk reduction?"* (NRC, 1997:11)

In the software, selecting "Technology Overview" from the main menu presents the history and current status of the technology. The discussion presents results of laboratory studies, pilot studies at Moffett Federal Airfield, and the full-scale field demonstration at Edwards Air Force Base. These studies and demonstrations all provide evidence that *in situ* aerobic cometabolic bioremediation reduces risk. The evidence that the technology

reduces risk is also presented in a consolidated format previously suggested in the NRC report (see Figure C-11).

Figure C-11. *In Situ* Aerobic Cometabolic Bioremediation: Risk Reduction and Cause-and-Effect Relationship (NRC, 1997:199)

Proving *In Situ* Bioremediation of Chlorinated Solvents at Moffet Naval Air Station, California

Researchers at Stanford University conducted a field study to demonstrate engineered *in situ* bioremediation of chlorinated solvents by methane-oxidizing bacteria (Roberts *et al.*, 1990;Semprini *et al.*, 1990). In this experiment, known quantities of vinyl chloride, trichloroethylene (TCE), *cis*-dichloroethylene (*cis*-DCE), and *trans*-dichloroethylene (*trans*-DCE) were injected into a densely monitored, well characterized aquifer. A series of biostimulation and bioremediation experiments was performed to document the engineered degradation of the organic solutes. Biostimulation by injection of methane- and oxygen-containing groundwater was used to stimulate the growth of indigenous bacteria. Results showed that biostimulation caused concurrent decreases in concentrations of the organic contaminants. The table below describes the types of data that were collected to (1) document remediation and (2) establish the cause-and-effect relationship between the methane-oxidizing bacteria and the documented remediation. In these experiments, controlled contaminant injections, conservative tracers, untreated test areas, systematic variation of operating parameters, and start-and-stop testing were used as controls.

Data Objective	Type of Data
Document reduction in quantity of contaminants	• Reduction in organic contaminant concentrations • Reduction in organic contaminant mass determined from the ratio of mean normalized concentration of organic contaminant to bromide tracer for quasi-steady-state conditions; a comparison of breakthrough of organic contaminants before and after biostimulation; and a mass balance comparing amounts of contaminant injected to amount removed at extraction wells
Link contaminant disappearance to indigenous methane-oxidizing bacteria	• Decrease of chlorinated organic contaminant concentrations coinciding with methane utilization • Production of a transformation intermediate for *trans*-DCE • Increase in organic contaminant concentrations and disappearance of transformation intermediate when methane addition stopped • Relative transformation rates consistent with laboratory data (vinyl chloride degraded faster than *trans*-DCE, which degraded faster than *cis*-DCE, which degraded faster than TCE) • No degradation of TCE observed in zone where no methane was present to support bacterial growth • No evidence of anaerobic conditions, i.e., no intermediate products of anaerobic degradation • presence of indigenous methantrophic bacteria

Software Dissemination: The screening software developed for *in situ* aerobic cometabolic bioremediation presents cost and performance data according to the recommendations of this thesis and the NRC (1997). The next appropriate step for the

software is to widely disseminate it to site owners. One method that is being pursued is through the Armstrong Lab Environics Directorate. As an Air Force leader in environmental remediation technology development, the Environics Directorate has access to all of the remedial project managers in the Air Force. As demonstrated in the NoVOCs case study, mailings to site owners are worthwhile. Additionally, follow-up phone calls to each individual who receives a copy of the screening software may be appropriate. Personal touches and extra effort, such as the site visits offered by Metcalf and Eddy to potential clients and regulators, often net substantial benefit. These are actions that fall within the domain of the technology champion.

Technology Champion

The results section of this thesis suggested that just demonstrating that a technology can reduce cleanup times and costs over traditional technologies is not enough to assure its transfer and widespread use in the commercial sector. A technology champion is vital to the progression of the technology. Because *in situ* aerobic cometabolic bioremediation has no clearly defined technology champion, the technology risks never being commercialized. Some of the technology developers have risen to the challenge on occasion. For example, Dr. Mark Goltz, one of the technology developers, had the *in situ* aerobic cometabolic bioremediation screening software developed in conjunction with this thesis. Another of the technology developers had a fact sheet distributed (Edwards Air Force Base, 1996). These actions demonstrate that interest exists among the technology developers to transfer the technology, but none has emerged as the technology champion. The results and conclusions of this thesis indicated that it may be appropriate

to clearly identify a technology developer involved with a particular environmental remediation technology to function as the technology champion. For *in situ* aerobic cometabolic bioremediation to successfully commercialize, this may be crucial.

Market Stimulation

Another area where a technology champion can have a large impact is in the commercial market. *In situ* aerobic cometabolic bioremediation offers a process that works and is significantly less expensive than traditional technologies. Technology vendors need to be educated on the benefits of the technology and the methods of employing it before it will gain widespread acceptance. Again, the developers have taken the appropriate action –a technology guide is in production that will outline methods of technology implementation as well as report on cost and performance data learned at the Edwards Air Force base demonstration. A technology champion could ensure that this document is provided to the appropriate people, in both the public and private sectors, and follow up with them to address any questions they may have. By educating private-sector firms through the use of the technology guide and fostering commercial interest, the technology champion can produce what could be called "technology transfer momentum." Vendors who gain interest in the technology and learn how to use it have a financial incentive to promote its use. Once this happens, as in the case of NoVOCs, much of the burden on the technology developer to publicize the technology is relieved. The private-sector firms offering the technology take over these responsibilities. And as can be seen in almost any market, when a new product catches on, others begin offering it –hence, more technology promotion by private-sector firms, not the developer.

World Wide Web Postings

An additional step that could be taken by the developers of *in situ* aerobic cometabolic bioremediation is increased postings on the internet describing the technology. At a minimum, the developers should post information about the technology at the Western Region Hazardous-Substance Research Center (which has aided in the development of the technology) site and at least one major data base such as that offered by the environmental division of the National Technology Transfer Center. Ideally, an internet site would be created that is strictly devoted to the technology. This site could offer internet access to the screening software, or at least an option to download it.

Conclusion

This appendix has explored *in situ* aerobic cometabolic bioremediation. We have reviewed its history, actions that are currently being taken to aid in its transfer, and actions that should be pursed in the future to help move the technology to the commercial sector.

The researchers involved with the development of the technology continue to make wise decisions to help transfer the technology. The technology guide currently in production will provide the needed instruction for technology vendors seeking to offer the technology to prospective clients. Furthermore, creating financial incentive within the commercial sector by training those interested in the correct way to employ the technology could provide technology transfer momentum. The development of the technology screening software presented in this thesis should provide site owners with an

easy way of determining whether *in situ* aerobic cometabolic bioremediation is appropriate for use at their site. Additionally, it offers sufficient flexibility, without being difficult to run, to allow the site owners to easily compare alternative technologies.

In situ aerobic cometabolic bioremediation has been shown to reduce risk and costs and the developers are making wise technology transfer decisions. Still, the transfer of the technology to full scale implementation is not guaranteed. The technology lacks a clear technology champion who will lead the technology through the barriers to technology transfer. Without an individual making follow-up calls and visits, the technology guide in production and the screening software may not get much attention by technology users, consultants, and regulators. The technology champion could also stimulate the market for *in situ* aerobic cometabolic bioremediation by helping to educate technology vendors on methods of implementation and by educating site owners on the cost and performancebenefits of using the technology. Developers of the technology should also seek to provide more access to information about the technology on the internet. The internet is becoming an often-used tool by regulators, consultants, and technology users who wish to learn about innovative technologies. Information should be offered on the Western Region Hazardous-Substance Research Center internet site and at a minimum, one of the large environmental technology data bases. The developers should also consider offering the screening software over the internet –either in a form that can be used over the internet or as a downloadable file. This could be one more step that sets the technology apart from other environmental remediation technologies –few, if any, developers have offered such a service on the internet.

While the additional steps addressed in this appendix should be taken to aid in the transfer of *in situ* aerobic cometabolic bioremediation, the technology is already well on the way to full-scale implementation. Probably the most significant thing that the technology lacks is a clear technology champion. The technology has all of the credentials of a "world class" technology and the cost and performance data from a full-scale demonstration to support that claim. Now all it needs is someone to show it to the world.

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13. ABSTRACT *(Maximum 200 words)*

The fact that an innovative environmental remediation technology has been proven feasible in a full-scale evaluation does not assure that the technology will be implemented. A number of regulatory, economic, and institutional barriers may impede the transition of a remediation technology from full-scale demonstration to implementation. This research explores these barriers, suggesting means to overcome them.

Regulators, technology users, and other remediation decision makers apply the nine criteria specified in the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) to evaluate the applicability of an innovative remediation technology at uncontrolled hazardous waste sites. These criteria consider such things as cost, implementability, and regulatory compliance of the technology. The usefulness of full-scale technology demonstrations to gather the data required under CERCLA for use by decision makers in evaluating an innovative technology for implementation is explored. Additionally, other mechanisms which may expedite transition of a technology to implementation, such as the use of patents and technology licenses are evaluated for utility. Likewise, the efficacy of information dissemination mechanisms, such as the Internet, are assessed.

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